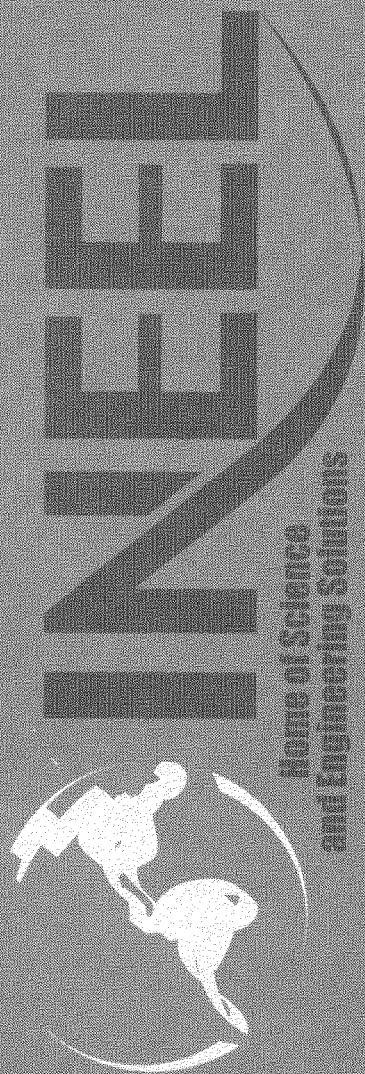


Evaluation of In Situ Vitrification for Operable Unit 7-13/14

*T. N. Thomas
Russell L. Treat
December 2002*



*Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC*

Evaluation of In Situ Vitrification for Operable Unit 7-13/14

**T. N. Thomas
CH2MHILL**

**Russell L. Treat
Dade Moeller and Associates, Inc.
under subcontract to CH2MHILL**

December 2002

**Idaho National Engineering and Environmental Laboratory
Environmental Restoration Program
Idaho Falls, Idaho 83415**

**Prepared under Subcontract No. K99-00000090
for the
U.S. Department of Energy
Assistant Secretary of Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727**

ABSTRACT

The Department of Energy is conducting the Waste Area Group (WAG) 7, Operable Unit 7-13/14 comprehensive remedial investigation/feasibility study at the Idaho National Engineering and Environmental Laboratory to satisfy the requirements of the Federal Facilities Agreement and Consent Order with the State of Idaho and the U.S. Environmental Protection Agency. The Comprehensive Environmental Response, Compensation, and Liability Act governs these activities, which involve assessments of contaminants of concern, risk factors, and potential technologies for remediating the site.

This report describes potential application of in situ vitrification to treat buried waste at the WAG 7 Subsurface Disposal Area radioactive waste landfill. Available in situ vitrification performance information is compiled to support evaluation of remedial alternatives. Applications of in situ vitrification and available technology performance data are summarized. An analysis of emerging configurations of the technology to evaluate applicability of this process to the Subsurface Disposal Area is included. Additionally, this report presents an analysis of available data to assess in situ vitrification effectiveness and implementability at WAG 7.

CONTENTS

ABSTRACT.....	iii
ACRONYMS.....	vii
1. INTRODUCTION.....	1-1
2. IN SITU VITRIFICATION TECHNOLOGY DESCRIPTION	2-1
2.1 History and Process	2-1
2.1.1 Starter Path.....	2-2
2.1.2 Melt Progression	2-4
2.1.3 Organic and Volatile Treatment.....	2-5
2.1.4 Off-Gas System.....	2-6
2.1.5 Melt Product Quality	2-6
2.2 Technology Options	2-8
2.2.1 Traditional In Situ Vitrification	2-8
2.2.2 Planar In Situ Vitrification.....	2-9
2.2.3 Plasma Arc In Situ Vitrification.....	2-11
2.2.4 Supplemental Technologies	2-12
3. SUMMARY OF IN SITU VITRIFICATION CASE HISTORIES	3-1
4. APPLICABILITY OF IN SITU VITRIFICATION TO THE SUBSURFACE DISPOSAL AREA	4-1
4.1 Implementability	4-2
4.1.1 Ability to Accommodate Variability and Uncertainty in Waste and Site Conditions.....	4-2
4.1.2 Ability to Prevent Melt Expulsion Events	4-5
4.1.3 Ability to Prevent Nuclear Criticality.....	4-9
4.1.4 Ability to Prevent or Control Underground Fires.....	4-9
4.1.5 Ability to Ensure Containment and Adequate Treatment of Hazardous Off-Gases	4-10
4.2 In Situ Vitrification Effectiveness	4-11
4.2.1 Short-Term Effectiveness	4-12
4.2.2 Long-Term Effectiveness	4-13
5. SUMMARY OF DATA GAPS FOR IN SITU VITRIFICATION	5-1
6. REFERENCES.....	6-1
Appendix A—Detailed In Situ Vitrification Case Studies	A-1

FIGURES

1.	Typical progression of a Traditional In Situ Vittrification melt (Lindgren and Phelan 2000).....	2-2
2.	Full-scale in situ vittrification melts performed per year.....	2-3
3.	Plan view of typical in situ vittrification starter-path configuration.....	2-3
4.	Cross-sectional and plan views of Planar In Situ Vittrification melt progression (graphics adapted from Los Alamos National Laboratory [LANL 2000])	2-9
5.	Subsurface Planar In Situ Vittrification (graphic from Los Alamos National Laboratory [LANL 2000])	2-10
6.	Plasma Arc In Situ Vittrification process configuration (graphic from Lindgren and Phelan 2000)	2-12

TABLES

1.	Relevant case history summaries	3-3
2.	Potential in situ vittrification data gaps and evaluations.....	5-1

ACRONYMS

HEPA	high-efficiency particulate air
INEEL	Idaho National Engineering and Environmental Laboratory
ISTD	in situ thermal desorption
ISV	in situ vitrification
MEE	melt expulsion event
PCB	polychlorinated biphenyls
PCT	Product Consistency Test
RCRA	Resource Conservation and Recovery Act
RFP	Rocky Flats Plant
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
TCLP	Toxicity Characteristic Leaching Procedure
TRU	transuranic
VOC	volatile organic compound
WAG	waste area group

Evaluation of In Situ Vitrification for Operable Unit 7-13/14

1. INTRODUCTION

The Idaho National Engineering and Environmental Laboratory (INEEL) is currently performing work in the feasibility study phase of the Comprehensive Environmental Response, Compensation, and Liability Act to address the waste buried at the Radioactive Waste Management Complex (RWMC), designated as Waste Area Group (WAG) 7. Within WAG 7 is the Subsurface Disposal Area (SDA), which has been the disposal site for various radioactive waste types from INEEL, Rocky Flats Plant (RFP), and other sources over the past 50 years. Currently, remediation alternatives for the SDA are being evaluated as part of the feasibility study. One of the goals of the feasibility study is to explore and evaluate different technologies that will protect human health and the environment. Those technologies must address site-specific conditions presented by the SDA, as summarized below.

The SDA opened in 1952 and is still in operation. Over the years, the SDA pits, trenches, and soil vaults received widely varying waste matrices, containers, and contaminants. Known contaminated matrices include paper, glassware, filters, pipefittings, plastic, sludge, soil, and activated metals. Irradiated fuel material or high-level radioactive waste also may have been deposited. Waste containers include cardboard boxes, wooden boxes, garbage cans, metal drums, and miscellaneous other packaging such as plastic bags. Previous studies (Becker et al. 1998) identify radionuclides, volatile organic compounds (VOCs), and nitrates as contaminants of potential concern.

The SDA pits, trenches, and soil vaults range from about 3 to 9 m (10 to 30 ft) in depth. These waste disposal systems were constructed through clayey lakebed deposits to the top of a massive basalt layer. Most of these disposal systems were unlined, though a layer of native clay soil was placed over the basalt in some areas before waste was deposited. In some areas, the soil was excavated mechanically, and, more recently, explosives were used to remove basalt and deepen low-level waste disposal pits. Pits 17–20, the deepest disposal pits, are 10 m (33 ft) deep (Farnsworth et al. 1999). These pits do not contain transuranic (TRU) waste and, hence, would not be treated with in situ vitrification (ISV), which currently is applicable to shallower waste sites. Several feet of native soil were used to cover the waste following disposal.

The variability of waste forms and disposal techniques will challenge any single remediation technique; however, as one of the technologies available for remedial actions at the SDA, ISV is applicable to a wide variety of waste types in specific SDA pits and trenches. The analysis in this report focuses on application of ISV in the pits and trenches in the SDA that received TRU waste from the RFP in the 1950s and 1960s, Pits 1-6 and 9-12, and Trenches 1-10. These disposal units exhibit characteristics that conform to the proven limits of ISV technology. Waste from RFP contains TRU waste and hazardous organics, salts, and metals that can be destroyed or immobilized within the glassy monoliths produced by ISV. Seven case histories for relevant projects performed within the previous 12 years are described in detail in Appendix A.

This report supports the *Preliminary Evaluation of Remedial Alternatives* (PERA) (Zitnik et al. 2002) and the future feasibility study detailing ISV's potential applicability to the waste and conditions documented at the SDA.

The five key objectives of this report are to:

1. Describe the process and status of ISV technology options that could be used to treat soil and buried waste at the SDA
2. Review recent case histories of ISV applications at other sites and apply relevant information to the evaluation of potential ISV methods at the SDA
3. Describe the advantages and disadvantages of ISV applications to the soil and buried waste at the SDA
4. Describe the effectiveness and implementability of treating soil and buried waste with ISV in applicable pits and trenches at the SDA
5. Identify ISV technology data gaps with respect to SDA conditions.

The discussion of data gaps describes treatability tests and other needs to fill the gaps and reduce uncertainties associated with using ISV technology at the SDA. A treatability test that would have combined bench-scale tests, a full-scale cold test, and a hot test on the north corner of Pit 4 was cancelled because of safety concerns and to allow performance of other priority work. Further analysis of waste-generation records and treatability testing may be necessary to design off-gas treatment systems that can assure conformance to emissions standards. Safety-related issues also must be addressed.

2. IN SITU VITRIFICATION TECHNOLOGY DESCRIPTION

2.1 History and Process

The American Geological Institute (1983) defines vitrification as the conversion of a substance into a glass or glasslike substance by fusion as the result of heat. In this definition, glass is “an amorphous product of rapid cooling of a magma.” Nonmetallic, inorganic materials containing significant levels of silica and a flux such as soda will melt and subsequently harden with relatively rapid cooling into a glassy solid similar to obsidian. Most soil and many waste materials will melt and form glassy solids upon cooling.

Since the 1950s, glass has been under consideration as a potential containment and stabilization medium for radioactive waste. Glass (primarily in the borosilicate form) is used at several locations around the world for immobilizing highly radioactive waste (NRC 1996). The advantages of glass as a waste form for radioactive and other hazardous waste materials include the following:

- The potential to incorporate a wide range of waste constituents in a highly stable, leach-resistant form
- The potential to destroy hazardous compounds by pyrolysis and other reactions resulting from the high temperatures reached in the glass-forming process.

In 1980, under contract to the U. S. Department of Energy, Pacific Northwest Laboratories in Hanford, Washington, began developing ISV, a vitrification technology capable of processing contaminated soils in situ (in place) (Buel et al. 1987). The process has undergone refinements over the years, but the fundamental soil-melting concept remains the same.

Briefly, the Traditional ISV process employs an array of four electrodes placed vertically 60 cm (24 in.) into the waste or contaminated soil. At the SDA, the electrodes would be inserted into clean soil above the waste to eliminate the risk of radioactive contamination during this step. High voltage is applied to the electrodes, resulting in the passage of electrical current through the soil between the electrodes. The heat generated from the resistance of the soil to the passage of the current is referred to as joule heating by the developers of the technology. As the heated soil melts progressively downward, the electrodes are allowed to sink through the melted soil, enabling melt depths of 6 m (20 ft) or more. Figure 1 presents a schematic showing the progression of a typical ISV melt.

An off-gas hood covers the entire melt and some distance around its outside edge to control the removal of gases and airborne particles generated within or near the melt. The off-gases are drawn into the off-gas hood by the negative pressure created by blowers and then treated in a process train before being discharged by a stack into the atmosphere. When the melt has progressed to the desired depth, the power to the electrodes is shutoff, and the melt is allowed to cool. Generally, the electrodes are left in place in the melt and sawed –off, at the ground surface. New electrodes typically are installed at each new melt location. The final melt is smaller in volume than the original waste and associated soil as a result of the following:

- Removal of volatile species by various reactions
- Reduced void space
- Higher density of glass relative to bulk soil and most waste materials.

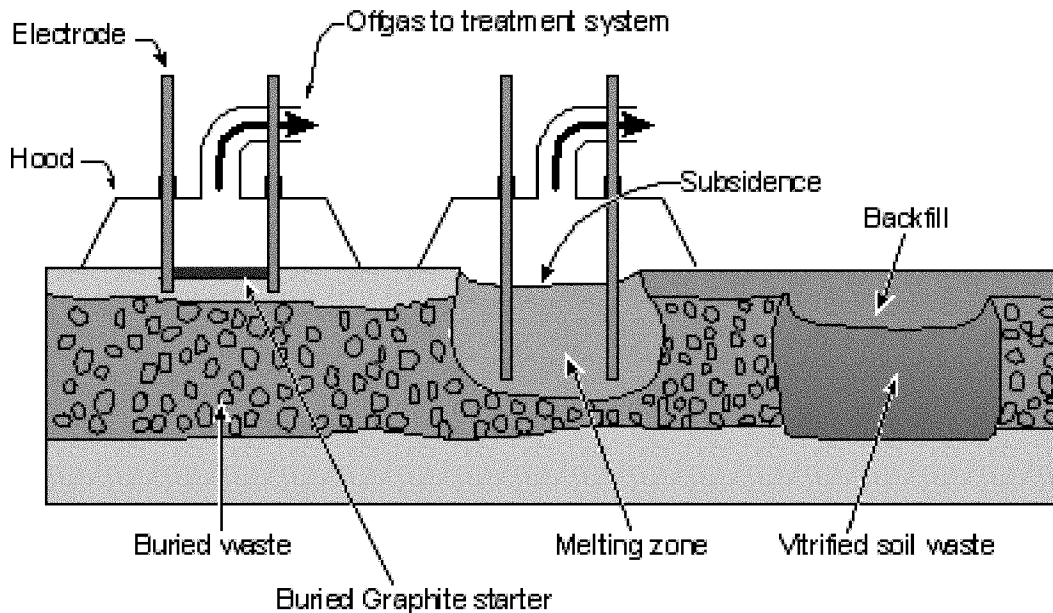


Figure 1. Typical progression of a Traditional In Situ Vittrification melt (Lindgren and Phelan 2000).

Each melt produces a single block-shaped monolith of glass. Most vitrification projects require multiple melts that overlap to some extent in order to fully treat the waste site. When a melt has reached sufficient depth, the ISV containment hood is moved and a second melt is produced at an adjacent or leap-frogged location. This process is repeated until the entire site has been vitrified.

The ISV process can immobilize extremely hazardous materials (including radionuclides) that may be difficult to treat by any other method. Incorporating contaminants into glass can effectively preclude their migration into environmental media (e.g., air, soil, and water). The massive block of glass created by ISV is an effective waste form because of its high leach resistance, low surface-area-to-volume ratio, and strong, nondispersible form. If the vitrified waste site is closed using a protective cover, the contaminants immobilized in the glass are further isolated and even less likely to harm human health or the environment.

The first commercial application of the ISV technology was at Parsons Chemical Plant in Michigan in 1993 as described in Kalb et al. (1997). Since then, nearly 100 full-scale melts have been performed on buried-weapons debris; contaminated soil; buried storage tanks containing dioxins, polychlorinated biphenyls (PCBs), and mixed radioactive waste; and other waste materials.

The graph in Figure 2 shows the number of full-scale melts performed each year since 1986.

2.1.1 Starter Path

The Traditional ISV process is initiated by inserting four electrodes into the earth in a square array. Full-scale ISV processes generally employ graphite or molybdenum electrodes approximately 30.5 cm (12 in.) in diameter, spaced 2–14 m (7–45 ft) apart. Generally, more closely spaced electrodes aid in achieving the greatest melt depths. The passage of current through the soil between the electrodes raises the temperature to that required for melting. Because soil is a relatively poor conductor of electricity, a mixture of graphite and pulverized glass (frit) is placed in trenches dug between the electrodes to serve as a conductive starter path. The starter path has a cross section of approximately 30 × 30 cm (12 × 12 in.). The initial flow of current between the electrodes occurs along these paths of lowest electrical resistance. A typical electrode- and starter-path configuration is shown in Figure 3.

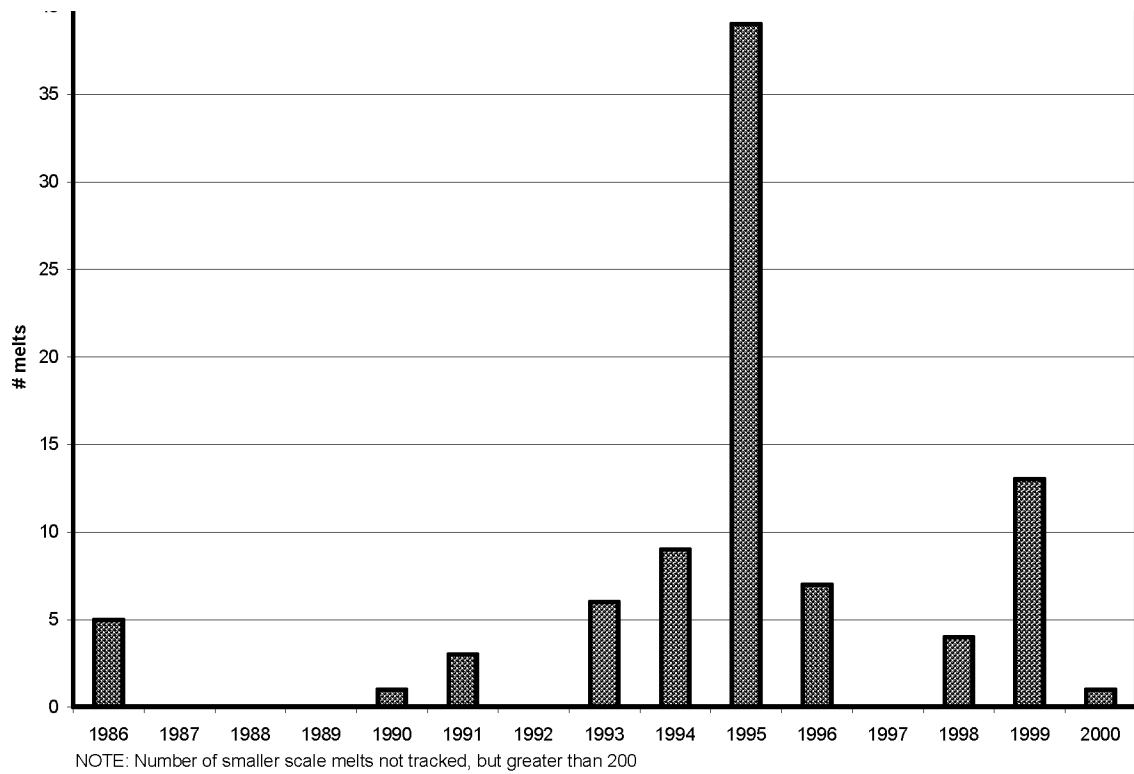


Figure 2. Full-scale in situ vitrification melts performed per year.

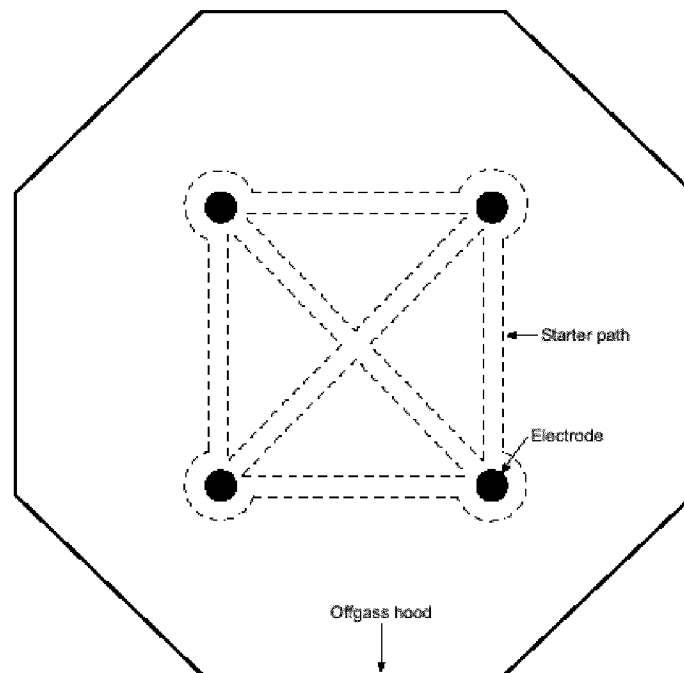


Figure 3. Plan view of typical in situ vitrification starter-path configuration.

2.1.2 Melt Progression

When voltage is applied to the electrodes, a flow of electrical current is established through the starter path. The resultant discharge of joule heat in the starter path generates starter-path temperatures of up to 2,000°C, well above the 1,100°–1,400°C required to melt soil. As frit in the starter path melts, adjacent soil begins to melt and mix with the molten frit. These events increase both the electrical resistance of the molten frit and the amount of energy dissipated at a given amperage level, resulting in higher melting rates (Buel et al. 1987). Because the energy dissipated is a direct function of both electrical current and resistance, the melt zone gradually widens and deepens. The typical soil temperatures during ISV processing are between 1,400°C and 1,600°C.

Electrodes may sink through molten soil under their own weight or, alternately, they may be held at the desired depth using mechanical clamps. Thermocouples embedded in the waste at varying widths provide the capability to monitor the growth of the melt. The thermocouples are connected electronically to a control trailer, where process operators can observe real-time waste temperatures. The thermocouples indicate increasing temperatures as the melt progresses until burning out at approximately 1,400°C.

Physical and chemical conditions of the waste site impact the achievable depth of a melt. Too much or too little silica or soda, for example, can restrict melt depth and reduce the quality of the glassy product. Shallow melt depths can be attained by holding the electrodes in place or by stopping the flow of current. As the size of a melt increases, the surface area of the molten mass in contact with unmelted soil and waste also increases until the amount of energy lost to cooling equals the amount added by joule heating. At this point, the melt stops growing. Melt depths of 6.7 m (22 ft) have been attained with the Traditional ISV application. Approximately 10–14 days are required to complete a melt.

The volume of a melt is usually less than that of the original waste and soil. Densification occurs because glass contains relatively few voids and because oxidation and pyrolysis during melting largely eliminate organic materials in the waste. A volume reduction factor of 30–70% is typical.

The masses of glass in full-scale melts have ranged from 200 to 1,400 tons. Final melt dimensions have ranged from 8.2 m (25 ft) in diameter by 0.7–1.0 m (2–3 ft) thick at the Wasatch site to 14.8 m (45 ft) in diameter by roughly 3.9 m (12 ft) thick at the Parsons Chemical site.^a

Several factors impact the applicability of ISV to a particular waste site as described in Kalb et al. (1997). These factors, which were developed for the traditional application of ISV, include the following:

- The depth of the buried waste should be within the demonstrated limits of the technology; otherwise, retrieval and restaging the waste in shallower configurations is required to ensure complete melting
- The alkali content should be within a 1.4 to ~15% range and ideally 2–5% to ensure a suitable melting temperature and product quality
- Voids should not exceed 2.5 ft³ to minimize potential for melt expulsions and poor control of the process

a. L. Thompson, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, “Results of In Situ Vitrification at Parsons Chemical Site,” January 9, 2001.

- No sealed containers, pockets of liquids, or wet silts/nonswelling clays should be present to minimize the potential for melt expulsions
- The combustible organic content of the waste should not exceed 10 wt% to ensure the combustion of gases produced during the pyrolysis of the organic materials in the hood will not produce high temperatures that exceed the current design limitations of the hood
- The elemental metals content of the waste should not exceed 37 wt% to prevent electrical shorting and ensure effective operations
- The inorganic-debris content of the waste should not exceed 50 wt% to ensure effective operations and high product quality
- The plutonium content of individual melt settings should not exceed 30 kg to preclude potential for a nuclear criticality
- The Cs-137 content of individual melt settings should not exceed a few curies to avoid undesirable worker exposure to ionizing radiation as a consequence of the relatively high volatility of Cs-137
- The waste site must have sufficient load-bearing strength to support the crane or other device required for moving the off-gas hood.

Several impediments to effective ISV processing are known. Excessively wet soil melts more slowly and requires higher energy input than dry soil as the temperature of the waste will not rise above 100°C until the soil moisture in the melting zone has evaporated. Melt expulsion events (MEEs), in which molten material is ejected from the melt with the release of pressurized gases, have occurred at several sites, as described in the case histories presented in Appendix A. These MEEs have been attributed to several different mechanisms, including water vapor trapped beneath the melt zone, melts progressing into sealed containers of volatile materials, and melts encountering unexpected, unexploded ordnance. It is unlikely that unexploded ordnance was disposed of at or used to deepen waste disposal sites at the SDA that are candidates for treatment by ISV, however. Consequences of MEEs include momentary losses of vacuum under the off-gas hood, hood fires, equipment damage, and emissions of untreated off-gases to the environment. Therefore, MEEs have been a major focus of research for this technology and are discussed in more detail in Section 4.1.

2.1.3 Organic and Volatile Treatment

Waste materials subjected to heat during ISV processing may evaporate, decompose, pyrolyze, react with water and waste chemicals, dissolve, or become physically encapsulated in the molten glass. Materials that evaporate, decompose, pyrolyze, or react usually produce gases that vent to the off-gas hood. Chemicals with boiling points below that of the melting point of soil will volatilize (given sufficient time) before the melt zone contacts the chemical. The boiling points and locations of such chemicals relative to the advancing melt may determine whether the chemicals are destroyed, vitrified, or remain in the subsurface adjacent to the melt. Volatile organic compounds with boiling points below 100°C may volatilize and condense in the soil beyond the 100°C isotherm where water is evaporating. Volatile chemicals also may flow around and upward from the melt zone in response to the negative pressure maintained in the off-gas hood (Dragun 1991). Semivolatile chemicals with boiling points above 100°C may progressively evaporate and condense within the dry zone between the advancing melt front and the 100°C isotherm. The flow of steam and other vapors in the subsurface around the melt will enhance removal of volatile and semivolatile chemicals by stripping and through reestablishing gas-to soil equilibria in accordance with Henry's Law.

Empirical data in one test showed that about 97% of VOCs, such as carbon tetrachloride, were destroyed during ISV; 3% were captured in the off-gas treatment system; and less than 0.1% remained in the soil surrounding the melt (Kalb et al. 1997). A small fraction of certain organic chemicals and salts may melt and migrate to some extent before they decompose or volatilize. Thus, some waste materials may not be completely destroyed or vitrified.

Measures that may minimize the potential for significant VOC residues after ISV include the following:

- Soil vapor extraction could be deployed near the melts during ISV processing to collect volatiles pushed outward from the melt zone.
- The melts could be initiated at the perimeter of a waste area and then progress inward. This would effectively circumscribe the zone containing VOCs and prevent them from migrating outward.

The use of a protective barrier over the vitrified site to limit water infiltration and intrusion by plant roots and animals would likely be effective in minimizing the environmental impacts of the small amounts of residual waste materials that escape destruction and incorporation within the glass monoliths.

2.1.4 Off-Gas System

The purpose of the off-gas system is to collect and treat hazardous gases and particles emitted during the melting process. The off-gas system consists of a protective hood that encompasses a significantly larger area than the projected area of the melt. A pressure of about -1.3 cm (-0.5 in.) water gauge is maintained in this hood at all times using blowers. Air intake represents as much as 99% of the total flow to the off-gas system (Kalb et al. 1997). The off-gas treatment train is designed to collect and treat the expected off-gas constituents and concentrations at each site.

Off-gas treatment units typically consist of quenchers, scrubbers, mist eliminators, heat exchangers, condensers, activated-carbon adsorbers, high-efficiency particulate air (HEPA) filters, and thermal oxidation units. The off-gas system is equipped with sampling ports along the treatment train to support regulatory and process-control monitoring. After the gases are treated to meet regulatory requirements, they are discharged to the atmosphere. The *Operable Unit 7-13/14 ISV Treatability Study Work Plan for the SDA* (Farnsworth et al. 1999) describes a planned radioactive ISV test (now cancelled) and the associated off-gas system design.

The effectiveness of an ISV off-gas treatment system is dependent upon the accuracy of the estimated off-gas contaminant types and quantities. Contaminant types likely to be present in ISV off-gases in the SDA application include VOCs that escape pyrolysis, acid gases, mercury vapors, and air-entrained particles. As with other remediation technologies, the ISV process is not recommended for sites at which the ranges in compositions of materials at individual melt settings are not well established or for which there is little basis for conservatively estimating off-gas constituent concentrations and generation rates. Conservatively designing the off-gas system and imposing restrictive operating conditions may be effective in managing these uncertainties, however. A conservative design also may be costly and may have adverse impacts on the processing capacity and schedule.

2.1.5 Melt Product Quality

Coring the cooled melt and testing core samples is the established method of measuring the quality of the melt product. Because a wait of about 1 year is required to cool a full-scale melt sufficiently to enable coring, melt quality results are delayed significantly.

The product quality of every full-scale melt tested to date has surpassed leachability and product consistency requirements that have been established for Resource Conservation and Recovery Act (RCRA) waste and high-level radioactive waste.^b These qualities consistently exceed those of borosilicate glasses produced in high-level waste vitrification plants in the U.S.^c Melt quality is usually measured by two tests: the Environmental Protection Agency 1998 Toxicity Characteristic Leaching Procedure (TCLP) and the American Society for Testing and Materials' Product Consistency Test (PCT) (ASTM 1997).

Leachability of certain chemicals under mildly acidic leaching conditions is measured by TCLP. This test, commonly used at EPA-regulated sites, is mandated for determining if a waste is toxic and if toxicity has been eliminated by treatment. The PCT is a commonly used test developed to assess the chemical durability of radioactive waste and simulated radioactive waste glasses. In the PCT, glass is crushed, sieved, and contacted with a specified leachant (usually water) for a specified time. The resulting leachate is then filtered and analyzed for glass components such as sodium. The amount of a targeted waste component in solution per surface area of glass exposed is calculated and compared to the total content of the glass. This ratio, when compared to ratios determined for natural glasses and glasslike materials such as basalt is an indicator of the long-term quality of the waste form.

The PCT was developed originally for testing borosilicate glasses, which melt at relatively low temperatures (about 800°C) and remain amorphous for the most part. High-temperature glasses of the type produced by ISV, however, tend to crystallize to a significant extent upon cooling. Sodium generally concentrates within the amorphous glassy fraction of ISV glasses. This fraction leaches more readily than the crystalline fraction. Therefore, the PCT leachability projections based on the release of sodium alone are conservative for ISV glasses.^d

Though widely used as indicators of the quality of waste forms, TCLP and PCT results do not represent the more aggressive leaching conditions that may be generated by chemical changes in leachate as it penetrates fissures or cracks at depth in the vitrified waste form. Such changes may be enhanced by relatively dry climates or when a barrier is used that limits infiltration of water. McGrail et al. (2000) describes other tests used to measure leach rates of waste glasses, including the Accelerated Dissolution Test. This test was designed to measure the dissolution rate of glass in the presence of its alteration phases and in a solution that is in near equilibrium with those phases. In one accelerated dissolution test reported in McGrail et al. (2000), an incubation period existed in which the dissolution rate was at first very low and then increased because of the effects of the alteration phases. Thus, additional testing may be needed to support long-term projections of contaminant releases from ISV glasses. For now, conservative (high) release rates are used to assess effectiveness, though actual performance could be substantially better.

Certain chemicals within the melt, primarily iron, may be chemically reduced to the metallic state by reaction with carbon present in the waste if sufficient iron salts or oxides are present. Iron oxide or salt contents of greater than 10 wt% are required for chemical reduction to metallic iron to occur. Any newly formed metals, along with molten metals formed by melting steel, lead, and other metals in the waste during ISV processing, sink to the bottom of the melt because their densities are higher than that of glass. Lead does not alloy readily with iron and may form as a distinct layer below the iron layer because of its

b. J. Hansen, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, "Full-Scale Melt Product Quality," January 12, 2001.

c. L. Thompson, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, "Melt Product Quality," January 9, 2001.

d. R. K. Farnsworth, Telephone communication with Tami Thomas, CH2M HILL, "Product Consistency Test," February 14, 2001.

higher density. Though metallic lead will not pass TCLP, the layer of iron and the glass above the lead layer will partially encapsulate the lead and limit exposure to infiltrating water to quantities that pass through cracks in the glass. The frequency of cracks in the glass is small as a result of the low thermal stresses induced by the very slow rate of cooling that occurs underground.

Some contaminants, such as plutonium and uranium, are not chemically reduced because of their high oxidation potentials. These chemicals are converted to or remain in the oxide form, which is incorporated in and distributed throughout the melt by convective mixing (Buelt et al. 1987).^e

The quality of the zone immediately surrounding the melt must also be considered since certain mobile chemicals and radiochemicals will be deposited in this region to some extent. These chemicals and radiochemicals include the following:

- VOCs that condense beyond the 100°C isotherm
- Low-melting-point salts that may partially seep into the soil beneath the melt
- Other salts, such as sodium sulfate, that may not be incorporated completely in the glass matrix because of low glass solubility
- Semivolatile metals, metal oxides, and radionuclides such as mercury, lead, cadmium, arsenic, and Cs-137 that evaporate and condense in the soil.

Low-melting-point salts and salts with relatively low solubilities in glass may partially fuse soil particles together, but the leach-resistance of such material would be poor. Condensation of semivolatile metals, metal oxides, and radionuclides will occur in a layer of unmelted soil around the melt if the range of temperatures within the layer is below the boiling point. The leach-resistance of condensed species also is expected to be poor; however, the quantities condensed are likely to be low because retention in the melt will be high, with the exception of species with a low boiling point, such as mercury. The application of a protective barrier over the site following ISV can limit water infiltration and, therefore, the mobility of such chemicals and radionuclides and the potential for their contact by plant roots and burrowing animals.

2.2 Technology Options

The evolution of ISV technology has resulted in three different configurations of the process:

- Traditional ISV
- Planar ISV (with or without subsurface initiation)
- Plasma arc (or bottom-up) ISV.

2.2.1 Traditional In Situ Vitrification

The Traditional ISV process was described previously. In summary, four electrodes are implanted a short distance into the ground and connected by a conductive starter path. Voltage is applied to the

e. Timmerman, C. AMEC-GeoMelt, telephone communication with Tami Thomas, CH2M HILL, "Convective Mixing of Oxides During Melt," February 12, 2001.

electrodes, causing current to travel preferentially through the starter path, heating and melting the conductive material. Adjacent soil falls into the path and is incorporated into the melt. This increases the electrical resistivity, which further increases the heat generated. As the melt advances downward, the electrodes gradually fall by gravity through the melted material. A final depth is reached when the current is stopped or when the surface area of the melt is high enough that cooling (primarily from the top surface) matches the energy input, effectively stopping further advancement of the melt.

2.2.2 Planar In Situ Vitrification

Like Traditional ISV, Planar ISV employs the same joule-heating principle but differs in the application of electrical current and in the starter-path configuration. In Planar ISV, current travels only between pairs of electrodes (rather than among all four electrodes), causing two parallel planar melts to form. As the melts grow downward and spread laterally, they eventually meet in the center of the electrode array and fuse together into one melt as shown in Figure 4. The final Planar ISV melt has approximately the same size and shape as a Traditional ISV melt.

A further adaptation of the Planar ISV technology is known as Subsurface Planar ISV. This adaptation, shown in Figure 5, initiates the melt zone below ground surface. In this configuration, the starter path is installed at the desired depth by placing starter-path materials in a deep trench or by injecting them at the desired starting depth. Subsurface Planar ISV tests to date have been initiated between 2 and 3 m (6 and 10 ft) below ground surface. Melts progressed downward from this depth.

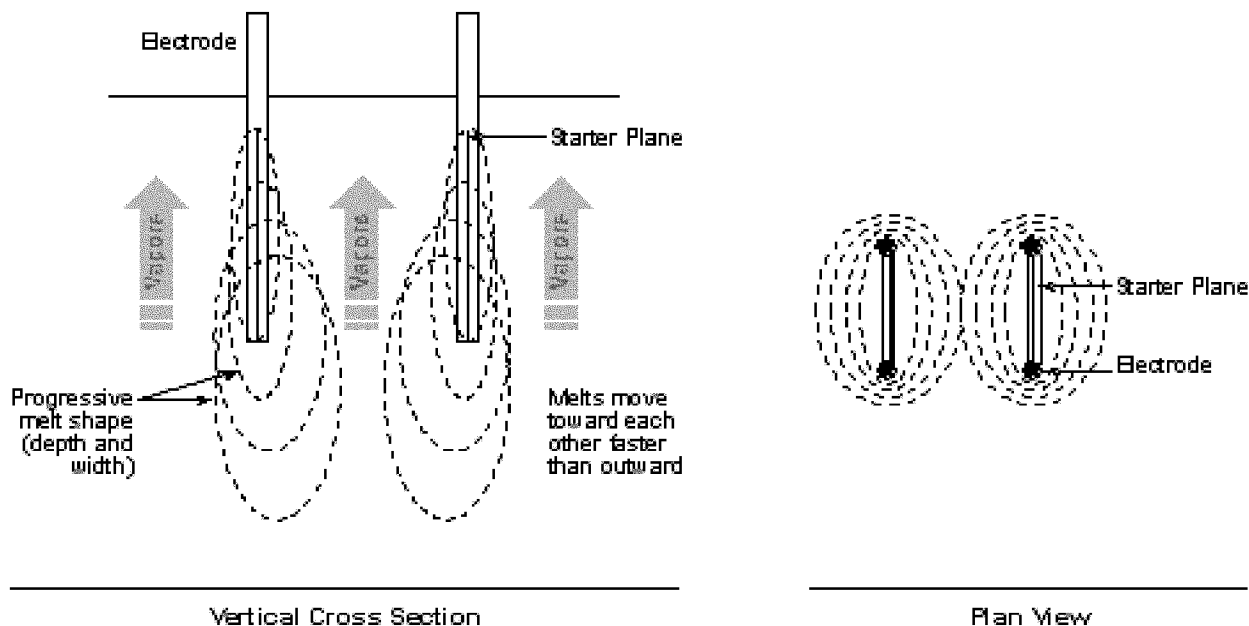


Figure 4. Cross-sectional and plan views of Planar In Situ Vitrification melt progression (graphics adapted from Los Alamos National Laboratory [LANL 2000]).

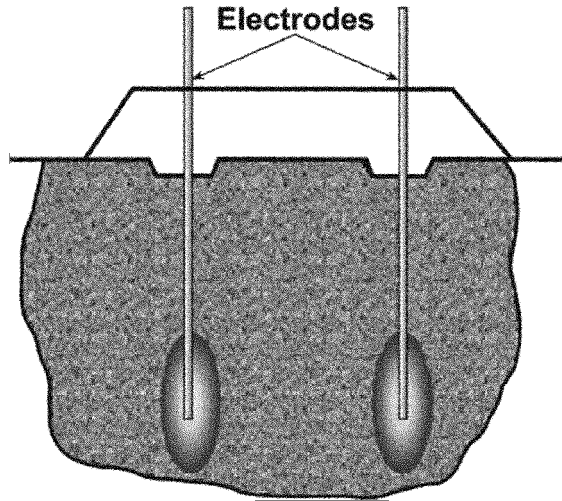


Figure 5. Subsurface Planar In Situ Vitrification (graphic from Los Alamos National Laboratory [LANL 2000]).

Primary benefits of Subsurface Planar ISV include the following:

- Lower off-gas hood temperatures, as the overburden effectively insulates the hood from the melt zone.
- Higher melting energy efficiency, as the insulation of the melt surface minimizes heat loss to the hood. (The normal energy consumption for an ISV melt is approximately 700 kW-hr/ton of processed soil. The energy consumption in the Subsurface Planar ISV test on the simulated INEEL V-tank was only 400 kW-hr/ton of processed soil [see Appendix A]^f).
- Enhanced protection of equipment and personnel at the surface, as the overburden provides a physical barrier to protect against MEEs and to filter gas-borne contaminants.

A disadvantage of Subsurface Planar ISV is the potential for semivolatile contaminants to condense and accumulate in the overburden soil. This condition has not been observed in the limited testing conducted to date but should be investigated when condensable materials are present in the waste.

Subsurface Planar ISV, though only recently applied, has the potential to extend deeper than Traditional ISV because of its higher melting efficiency. Melting depths of about 8 m (25 ft) apparently were achieved in recent cold and hot tests conducted with Subsurface Planar ISV at Los Alamos National Laboratory with capacity in reserve to melt deeper (Thompson et al. 2001). The reported maximum depth of some of the pits or trenches at the SDA is 10 m (33 ft) (Farnsworth et al. 1999) though the depths of RFP TRU pits and trenches for the application of ISV would be within the depth range that has been successfully demonstrated.

The Subsurface Planar ISV configuration also has the potential to reduce the likelihood of MEEs caused by melting around and trapping water-saturated clays or sealed vessels and voids. The unmelted

f. R. K. Farnsworth, INEEL, Telephone communication with Tami Thomas, CH2M HILL, "Energy Consumption of an ISV," February 14, 2001.

area between the electrodes provides a channel for safer release of pressurized gases and the interconnected porosity of the soil cap provides space into which the gases can compress and then be safely released to the off-gas hood.

The importance of the safe release of pressurized gases was demonstrated in nitrate explosive testing at the INEEL (Dick 2001). This testing was implemented in 2000 to evaluate the effects of heat generated during ISV processing on mixtures of nitrate salts and oil, graphite, charcoal, and cellulosic materials. The reactivity of nitrate-soaked rags was also studied. This program was initiated out of concern that combinations of waste materials known to be present in the SDA may react explosively during ISV processing. In order to simulate bounding conditions for potential explosive reactions, nitrate mixtures in 55-gal drums were pyrolyzed as a means of representing the pyrolyzing effects of an approaching melt. The drums were then sealed, instrumented, and buried to a depth of 3 m (10 ft). The buried drums were then heated at the 100°C per hour rate expected during ISV processing. These conditions caused explosive deflagrations in several cases. In one test involving the maximum amount of nitrates and pyrolyzed rags that could be contained in a drum, the 3-m (10-ft) cover of soil was breached. In other more probable test configurations, cracks were observed at the surface of the cover following the deflagrations, indicating that the force of the deflagrations was nearly sufficient to breach the cover. Dick (2001) concluded that the explosive effects of the maximum credible combination of nitrates and carbon sources tested in one drum can be mitigated by 3 m (10 ft) of soil overburden. Dick (2001) also concluded that the simultaneous deflagration of more than one drum was unlikely. Other potentially more energetic reactions, such as steam explosions, have neither been tested nor fully evaluated to date. Thus, care must be taken in projecting the ability of a 3-m (10-ft) soil cover to mitigate all possible MEEs.

The results and conclusions from this test were important factors in selecting the Subsurface Planar ISV option as the basis for the further development of the ISV alternative in this report.

2.2.3 Plasma Arc In Situ Vitrification

Plasma Arc ISV is a newer and much less tested technique. Based on established plasma arc technology, this method applies direct current between two electrodes within a torch, creating plasma consisting of highly ionized gases at very high temperatures. The resistance to the flow of current between the two electrodes generates the plasma (Mayne, Burns, and Circeo 2000).

In a recent field test of Plasma Arc ISV, a 1-MW plasma torch was lowered into a predrilled borehole to a depth of 3 m (10 ft). The torch heated the waste materials exposed in the hole, pyrolyzing the organic fraction and vitrifying the inorganic fraction, as the torch was gradually moved upward. Figure 6 shows a schematic of the Plasma Arc ISV application.

While this bottom-up ISV technology is experimental and has not been developed to the level of other ISV methods, it may have advantages over the top-down approach employed in Traditional and Planar ISV applications. A primary advantage is vapors and gases escape the subsurface above the melt zone and are not trapped beneath it. As a result, the use of Plasma Arc ISV may reduce the likelihood of MEEs. The extremely high operating temperatures generated by this technique may result in much higher volatilities of waste species, such as Cs-137, thereby increasing demands on the off-gas system. Another disadvantage of this technology compared to Traditional and Planar ISV is the application of energy only to the walls of the cored hole rather than within the waste mass. Heat is transferred into the waste by the slow process of conduction rather than by convective mixing of the molten glass. Convective mixing of the molten glass as occurs in Traditional and Planar ISV applications also ensures a much more homogeneous melt and largely eliminates concerns that pockets of the waste may be inadequately treated.

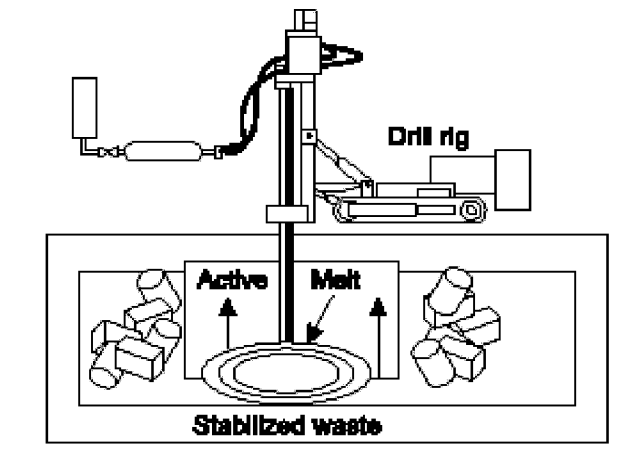


Figure 6. Plasma Arc In Situ Vittrification process configuration (graphic from Lindgren and Phelan 2000).

2.2.4 Supplemental Technologies

The selected ISV technology for this report, Subsurface Planar ISV, must be integrated with several supplemental technologies to form a safe and effective ISV alternative. Additional evaluation of bounding conditions is needed to identify final supplemental technologies. A summary of data gaps that should be addressed is provided in Section 5. Supplemental technologies would address following:

- Means of pretreating RFP TRU pits and trenches to eliminate MEEs and explosions within the off-gas hood. . In situ thermal desorption (ISTD) and a 3-m (10-ft) soil cover were selected since the ability of ISV alone to satisfy these needs has not been demonstrated at the SDA. However, evaluation of bounding conditions (e.g., steam explosions, fires, and ruptured compressed gas cylinders) as recommended in Section 5 may show that ISTD is not needed if, for example, a thicker cover and slower ISV processing are used.
- Means of treating off-gases generated during ISTD and ISV to meet emissions standards. Off-gas treatment trains consisting of HEPA filtration, activated carbon adsorption, wet and dry scrubbing, thermal oxidation, selective catalytic reduction, evaporation, and other processes were selected to satisfy this need.
- Means of treating secondary waste generated when treating ISTD and ISV off-gases to satisfy solid-waste disposal standards. Grouting of scrubber solutions and sludge (with disposal in a lined and covered settling basin), amalgamation of mercury, ISV of TRU-contaminated equipment, and onsite disposal of process-generated solid low-level waste and suitably treated mixed low-level waste were selected to satisfy this need.
- Means of protecting and isolating the grouted and vitrified areas upon completion of ISV processing. A Modified RCRA Subtitle C cap placed over these areas was selected to satisfy this need.

Brief descriptions of these supporting technologies follow. Rationale for their selection is provided in Section 4.

2.2.4.1 *In Situ Thermal Desorption.* The ISTD process heats soil and buried waste using an array of heated rods inserted into the soil and waste. Electrical resistance heating elements are typically used to heat the rods. Applications to date have been implemented to a depth of 6 m (20 ft), though a 24-m (80-ft) deep application is being planned. The waste and contaminated soil are heated to temperatures between 600°F (316°C) and 1,000°F (537°C) to vaporize and destroy most organics. Achieving temperatures up to 800°F (426°C) may take 3 months or longer. An aboveground gas collection and treatment system destroys or captures the remaining organics and vents carbon dioxide and water to the atmosphere.

2.2.4.2 *Grouting.* Grouting employs a high-shear mixer to blend liquid waste and grout formers (often Portland cement and other additives) to form a grout slurry. The slurry is added to drums or is pumped to a lined basin where it is allowed to harden. The high pH environment of grout is effective for immobilizing many heavy metals.

2.2.4.3 *Amalgamation of Mercury.* Mercury can be immobilized by intimately mixing it with various chemicals such as elemental sulfur or zinc to form an amalgam. A paint shaker or other high-energy mixer is used (LMITCO 1997).

2.2.4.4 *Onsite Disposal of Low-Level Waste.* The INEEL CERCLA Disposal Facility will open and begin accepting shipments of low-level waste in 2003. The disposal facility will be located at WAG 3 at the INEEL. The facility is designed with a triple liner and other features enabling disposal of low-level waste and treated mixed low-level waste.

2.2.4.5 *Modified Resource Conservation and Recovery Act Subtitle C Cap.* A cap consisting of low-permeability soil or clay, gravel, cobbles, and other geologic media provides protection against intrusion into contaminated media by animals and plant roots and limits the amount of infiltrating water that may contact the waste zone.

3. SUMMARY OF IN SITU VITRIFICATION CASE HISTORIES

In situ vitrification has been tested and applied for the past 15 years at several federal and commercial sites. The results of these projects indicate ISV, specifically Subsurface Planar ISV, may be an effective remediation for TRU waste at the SDA. Case histories for seven of the most relevant projects are summarized below. Table 1 and Appendix A provide additional detail on these projects.

- Oak Ridge National Laboratory WAG 7 Demonstration Melt, 1996: Traditional ISV was tested on a radioactive seepage pit
- General Electric's Apparatus Service Shop Melts in Spokane, Washington, 1994 and 1996: Traditional ISV was used at a commercial site for the remediation of soil contaminated with PCBs
- INEEL Full-Scale Test Demonstration, 1998: Subsurface Planar ISV was demonstrated on the Test Area North V-Tank
- Maralinga Test Range Plutonium Remediation Melts, 1998–1999: Full-scale Traditional ISV was performed on buried plutonium-contaminated waste
- Los Alamos National Laboratory Cold and Hot Tests, 1999–2000: Subsurface Planar ISV was tested on radioactively contaminated adsorption beds
- Brookhaven National Laboratory Organic-Surrogate Vapor Emissions Pilot Melt, 1996: The volatility and destruction efficiencies of organic tracers and mobility of radionuclide surrogates was measured during a pilot-scale Traditional ISV test
- INEEL Intermediate ISV Field Tests on Buried Waste, 1990: Intermediate-scale Traditional ISV tests were conducted on simulated waste typical of waste buried at the SDA.

The test at Oak Ridge National Laboratory demonstrated the importance of dewatering relatively impermeable and water-soaked clayey soils at the base of the melt to minimize the likelihood of an MEE. This test also demonstrated the potential for relatively high volatility of Cs-137 from a melt with an exposed surface.

The remediation of the Apparatus Service Shop Site demonstrated the ability to melt waste types such as drums, concrete, and asphalt that are present at the SDA.

The INEEL V-tank test successfully demonstrated Subsurface Planar ISV of a buried storage tank containing water and nonradioactive cesium to simulate Cs-137, an isotope present at the SDA.

The remediation of 13 melts at the Maralinga site demonstrated airborne plutonium contamination could be successfully contained during normal ISV processing of waste similar to that buried in the SDA. Waste at the Maralinga site included heavy structural steel, clothing, drums, lead, beryllium, barium, and plutonium. An explosion that occurred on the final melt demonstrated the importance of avoiding unexploded ordnance and gas cylinders in a Traditional ISV melt.

The tests at Los Alamos National Laboratory successfully demonstrated Subsurface Planar ISV over a rock stratum (tuff) that has the potential to limit water drainage in the same manner as the basalt layer that underlies the SDA. Waste species in common with the SDA included americium, plutonium, uranium, strontium, cesium, and tritium. This test also demonstrated the deepest melting achieved to date 8 m (25 ft) with deeper melts likely achievable since the test was terminated when the remedial action

objectives were met. Moreover, the cold-cap bridging that occurred during the test demonstrated the need for an overburden material that does not bridge or for a means to frequently disrupt the overburden to preclude bridge formation.

The tests at Brookhaven National Laboratory demonstrated that very volatile organic compounds such as acetone partially migrate into the soil beneath and around the melt and that most vaporize from the melt without being destroyed by pyrolysis. These results show the need to select off-gas treatment components for the SDA system that are capable of destroying or capturing volatile organics and the need to use a surface barrier over the completed melts to limit the mobility of and accessibility of biota to the residual volatile and semivolatile contaminants.

The INEEL tests on buried waste similar to waste disposed of at the SDA demonstrated that such waste is capable of MEEs and highly variable off-gas release rates, thereby demonstrating the need for a robust hood design and off-gas system and the need to use conservative operating parameters, such as additional soil cover and slower processing rates.

Table 1. Relevant case history summaries.

Owner/Site/ Location	Date Melted	Source Term	Contaminant Characteristics	Final Melt Depth and Size	Depth to Groundwater	Final Product Quality	Results	Comments
Oak Ridge National Laboratory WAG 7, Pit 1 Oak Ridge, Tennessee (LMITCO 1998)	Traditional ISV April 1996	Cs-137 and other radionuclides	Radioactive waste sludge in crushed limestone or dolomite matrix, capped with clean soil and asphalt cap.	7 ft deep ~20 ft ³	<10 ft	Easily passed toxicity characteristic leaching procedure, difficult to find anything left in melt to leach. Historically excellent product quality (B. P. Spalding 2001a).	Upheaval of steam and molten glass resulting in fire of peripheral equipment and insulation hoses. Minimal loss of off-gas containment.	Experimental melt. Project discontinued after explosion at end of melt. MEE caused by melting into barrier with very high moisture content. Base similar to Subsurface Disposal Area basalt. 17 days to MEE.
General Electric Co., Apparatus Service Shop Spokane, Washington	Two Traditional ISV melts: 1994—National Toxic Substances Control Act Demo. 1996—Remediation	PCBs	Gravelly sand “typical Spokane aquifer material.”	~16 ft deep	60 ft to 70 ft	Not cored, but sampled hot. Results acceptable.	No further action—Ecology happy with process.	Ecology regulated. Guy Gregory—Ecology: “Site was perfect for technology. Melt performed in middle of town, very quiet, no complaints. Only public comments were ‘gee whiz.’”
Idaho National Engineering and Environmental Laboratory, conducted at Richland, Washington (LMITCO 1998)	Subsurface Planar ISV April 1998	Simulated Waste Tank with Cs sludge and 33% volume water content	Sludge in an 8-ft-diameter, 12-ft-long storage tank (grain size unknown).	19 ft deep (20 ft×28 ft)	NA	No PCT was done. Glass passed TCLP for contaminant surrogates.	Melt went well. Tank was vented.	Planar ISV and buried waste melt. Starter path placed between 10 ft and 14 ft below ground surface. Results indicate effective ISV processing of buried storage tanks when vented.
Australian Government, Maralinga Test Range Taranaki, Australia (Borschman 2000)	Traditional ISV October 1998 through March 1999	Plutonium	Debris in buried pits blasted out of limestone and dolomite rock (steel, instruments, bricks, clothing, cables, drums, etc., mostly thick steel beams, some soil). Possible buried drum/box explosives or gas cylinder.	10 to 13 ft deep	Very deep, not encountered	Excellent—easily passed PCT ^c .	Explosion March 21, 1999, shut down technology. Investigation by Geosafe indicated buried explosives or gas cylinder.	Waste was silica-lean/metal-rich. 2.5 m to 3 m of sand was placed over pits to improve product quality. Project discontinued after explosion on 13th melt. Explosion probably caused by buried explosives or pressurized gas cylinder.
Los Alamos National Laboratory, TA-21 Los Alamos, New Mexico (Thompson et al. 2001)	Traditional ISV Cold Test—1999 Hot Test—April 2000	Inorganics, heavy metals, radionuclides (americium, plutonium, uranium, strontium, and technetium)	Adsorption beds from nuclear laundry. Particle sizes include cobbles, gravel, and sand.	Cold Test-25 ft deep Hot Test > 25 ft deep	~300 ft	Coring tentatively planned for August 2002.	Cold cap formed initially causing 2-week delay; the cap had to be cooled and broken in before melting resumed.	Hot test report currently in preparation. Illustrates effectiveness of Planar ISV configuration on increased depth. Application to Subsurface Disposal Area needs demonstrated ability to maintain 10-ft cover and ability to monitor cover thickness during melt. Cold test took 8 days.
Brookhaven National Laboratory, Upton, New York (Dietz et al. 1996; Fuhrmann et al. 1996)	Traditional ISV June 1996	Acetone, perfluorocarbon, and simulated radioactive tracers	Simulated laboratory waste, including bottles, cans, and debris (broken glass, crushed metal, and smashed plastic containers).	6 ft deep	Shallow, but not encountered	Excellent, though results of Accelerated Leach Test indicated increasing rates after initial “wash off” period.	Melt successfully produced for the purpose of assessing fate of volatile organic compounds and simulated radionuclides.	Greater than 85% of the acetone in the waste pit was emitted to the hood. Residual volatile organic compounds content in the soil gas increased with depth. 1.7% of the cesium tracer was found in the soil; cause was attributed to vapor phase transport.
Idaho National Engineering Laboratory, Water Reactor Test Facility Idaho Falls, Idaho (Callow et al. 1991)	Traditional ISV June to July 1990	Nonradioactive tracers	Drums and boxes containing simulated, typical buried waste at the Subsurface Disposal Area, including steel, concrete, and sludge.	Test 1: 8 ft Test 2: 11 ft	Very deep, not encountered	4 to 10 times more durable than typical high-level waste borosilicate glass per MCC-1 leach test.	Vigorous off-gassing and electrical instabilities encountered, resulting in MEEs “hissing” and “popping.”	Results of the test indicated that a good product was formed but that the process was more unstable than in previous tests. Though needed improvements were identified, the tests demonstrated the potential for ISV in Subsurface Disposal Area applications.

Owner/Site/ Location	Date Melted	Source Term	Contaminant Characteristics	Final Melt Depth and Size	Depth to Groundwater	Final Product Quality	Results	Comments
a. B. P. Spalding, Oak Ridge National Laboratory, Telephone communication with Tami Thomas, CH2M HILL, "Product Quality in Melt," January 4, 2001.								
b. G. Gregory, Telephone communication with Tami Thomas, CH2M HILL, January 4, 2001.								
c. L. Thompson, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, "Cold Test Results," January 9, 2001.								
ISV = in situ vitrification								
WAG = Waste Area Group								
MEE = melt expulsion event								
TSCA = Toxic Substances Control Act								
PCBs = polychlorinated biphenyls								
PCT = Product Consistency Test								

4. APPLICABILITY OF IN SITU VITRIFICATION TO THE SUBSURFACE DISPOSAL AREA

The primary advantage of ISV technology for the SDA application lies in the high quality of the glassy product. The ISV waste form is likely to be protective of human health and the environment for thousands of years (Buelt et al. 1987). Maintenance of this waste form is not required, and future-monitoring requirements, beyond confirming that the entire waste zone has been adequately treated, would be minimal. Moreover, ISV removes or destroys most hazardous organic materials, though uncertainties remain as to whether some VOCs would condense in soil adjacent to the ISV melt zone. In situ vitrification also decomposes most salts and encapsulates most metal oxides and radionuclides in the glassy product. Again, uncertainties remain about quantities of semivolatile metals, such as lead, and radionuclides, such as Cs-137, that also may condense outside the ISV melt zone. Some low-melting-point salts, such as sodium nitrate and potassium nitrate (melting point of their eutectic is 220°C), may not completely decompose, and a small amount may migrate away from the glass. A substantial fraction of metallic waste will melt and pool at the base of the melt and will not be incorporated into the glass matrix. The leach-resistance of some toxic metals, such as lead, which may form as a pool below the predominantly iron pool, would be relatively low.

Though the technology can process a wide range of waste types, limits regarding the types and quantities of waste have been established for melt depth, alkali content, void size, sealed containers, combustible content, metal content, inorganic-debris content, fissile-material content, and Cs-137 content (Kalb et al. 1997). These limits, which were developed for Traditional ISV, were defined in Section 2.1.2. A comparison of the information on SDA waste to these limits indicates the average SDA waste composition is likely to meet most of the conditions, assuming the waste is diluted with at least 50 wt% soil as should occur in most cases; however, every melt setting would not conform to all limits. Because these limits were developed for Traditional ISV, some may not apply to or may be relaxed for Subsurface Planar ISV applications. Subsurface Planar ISV has not been tested under many of the conditions expected at the SDA, and the ability to implement the technology and technology effectiveness are generally unproven. Additional treatability testing may be required to address data gaps as discussed in Section 5 and to provide the design, safety, and operating bases for ISV and its supporting technologies for SDA application.

The primary disadvantage of applying any form of ISV at the SDA is the uncertainty associated with its safe operation. Questions regarding the potential for MEEs, underground fires, and criticality events—all situations that could increase short-term risk of exposure to chemical and radiochemical contamination—cannot easily be answered with the information available today. Moreover, Subsurface Planar ISV, which holds promise for mitigating some of the safety concerns for the SDA, has not been tested under conditions that would bound the range of safety concerns related to the application of ISV at the SDA. Tests that might have provided some of the needed information (Farnsworth et al. 1999) were cancelled in 2001. Over-design of the off-gas treatment train may be required if safety uncertainties are not resolved. This could greatly increase capital and operating costs. Should Subsurface Planar ISV technology be a remediation alternative selected for WAG 7, testing and analysis would be needed to support design and operations.

Issues regarding the application of ISV at the SDA are summarized in following discussions of implementability and effectiveness.

4.1 Implementability

The implementability of Subsurface Planar ISV at the SDA is primarily determined by the ability to:

- Accommodate variability and uncertainty in waste and site conditions at the SDA
- Prevent or control MEEs
- Prevent nuclear criticality
- Prevent or control underground fires
- Contain and adequately treat hazardous off-gases and entrained particles.

4.1.1 Ability to Accommodate Variability and Uncertainty in Waste and Site Conditions

As summarized in Table 1 and as more fully described in Appendix A, relevant full-scale ISV projects have been performed under a wide range of waste and soil conditions that represent some of the conditions expected at the SDA. Known and postulated conditions that may impact the implementability of ISV at the SDA include the following:

- Variable depth of buried waste, ranging to 10 m (33 ft) (Farnsworth et al., 1999), though depths the RFP TRU pits and trenches are within the proven range of the technology
- Series 745 sludge, a mixture of salts consisting of 60% sodium nitrate, 30% potassium nitrate, and 10% miscellaneous material (Arrenholz and Knight 1991)
- Combustibles content of ~20 wt%, not including soil added during disposal (Arrenholz and Knight 1991)
- Metals content of ~22 wt%, including presence of large metal equipment, such as metal-working machines, cranes, vehicles, and disposal boxes
- Inorganic debris content of ~11% (Arrenholz and Knight 1991)
- Several hundred curies of Cs-137 and Co-60 in sources and potentially irradiated fuel materials
- Large voids in drums, boxes, and contaminated equipment, likely ranging from 5% to 90% of individual container volumes
- Partially compacted and uncompacted buried waste
- Large quantities of sealed drums containing wet Series 742 sludge, organic-bearing Series 743 sludge, occasional sealed bottles containing liquids, and possible gas cylinders (Clements 1982)
- Silt and clay underburden with relatively low permeability and potentially saturated with water (Farnsworth et al. 1999)

- Plutonium contents of individual drums as high as 2 kg (Woods and Neeley 2001) but averaging about 400 nCi/g
- Toxic metals, including arsenic, barium, beryllium, cadmium, chromium, lead, lithium, mercury, selenium, silver, thallium, and zirconium (Arrenholz and Knight 1991)
- Toxic organics, including PCBs and solvents, such as carbon tetrachloride and trichloroethane (Arrenholz and Knight 1991).

These conditions and the ISV limits for Traditional ISV discussed in Section 2.1.2 serve as bases for evaluating implementability.

4.1.1.1 Melt Depth Limitation. The maximum melting depth achieved to date is 8 m (25 ft) in the test of Subsurface Planar ISV at Los Alamos National Laboratory (see Appendix A). Though greater depths were likely achievable, the test was stopped at 25 ft because remedial action objectives were met. Assuming ISV would be limited to the RFP TRU waste in Trenches 1–10, Pits 1–6 and 9–12, and Pad A (following restaging of its waste in a new pit), no additional testing or technology development is required to demonstrate that melt-depth limitation can be met. A depth of 11 m (35 ft) or greater may be required to immobilize all of the waste and contaminated underburden at the SDA, if desired. This may be achievable with Subsurface Planar ISV by injecting the starter path beneath the overburden and maintaining at least 3 m (10 ft) of overburden to minimize cooling losses.

4.1.1.2 Alkali Limits. The alkali content of the clayey silts at the SDA falls within the ideal range for ISV (i.e., 2–5%). Approximately 30,000 drums of RFP Series 745 sludge (salt waste) were sent to the SDA. Their distribution in the SDA is roughly known through shipping and disposal records. About half of the Series 745 sludge is on Pad A, with the remainder in the pits. The presence of a high concentration of Series 745 sludge drums at particular melt setting could raise the alkali content to above the acceptable limit (~15%). A likely impact of excessive alkali levels is failure to achieve the desired melt depth because increasing the alkali content reduces the electrical resistivity of the melt, thereby limiting the energy input to the melt. Another likely impact is poor product quality because high alkali levels cause glasses to be highly leachable. Tests to evaluate the highest alkali salt concentrations anticipated for a single melt setting at the SDA may be required to verify that ISV can successfully process waste containing elevated alkali levels. Alternately, a method for injecting silica into the melt to ameliorate a high alkali melt may be required.

4.1.1.3 Combustibles Limit. The 20 wt% average combustibles in the waste (Arrenholz and Knight 1991) suggests the likelihood of pockets of combustibles above the 10 wt% limit after assuming the combustibles are mixed with 50 wt% soil. The potential for combustion of flammable gases produced from pyrolysis of organics during ISV in the hood or off-gas train, therefore, would be elevated for some melt settings. Further definition of the bounding thermal content and rate of generation of such gases at the SDA would be necessary to define specifications for the hood and off-gas train to preclude a fire or explosion in the hood. Of particular concern is the ability of the system to safely accommodate the sudden release of the contents of a waste cylinder filled with acetylene or propane into the hood.

The use of ISTD is assumed necessary as a preconditioning step for ISV to remove combustible gases and reduce the risk of fire and MEEs. Additional analysis and testing of Subsurface Planar ISV without ISTD, but under conservative operating and design conditions, may demonstrate that ISV can be safely implemented without pretreatment. However, ISTD was assumed necessary to directly address ISV safety-related issues that have not been fully resolved. The ISTD technology is a promising method of eliminating VOCs, depressurizing sealed containers and gas cylinders containing flammable liquids, and partially pyrolyzing other organics, thereby reducing the water and combustibles content of the buried

waste to the required level for safe and stable ISV operations. The use of this technology would significantly reduce the potential for MEEs (see Section 4.1.2). Pretreatment also would greatly reduce energy requirements for ISV melting by removing water, which requires a substantial application of energy to evaporate it. The overall energy requirements for combined ISTD and ISV processing would be increased above that required for ISV alone, however. The ISTD technology entails inserting heating rods into the waste and underburden on 2-m (8-ft) centers. Approximately 3 months would be required to heat the subsurface to greater than $\sim 360^{\circ}\text{C}$, the temperature necessary to ensure gas cylinders have discharged their contents (Farnsworth et al. 1999) and to vaporize most of the mercury. Achieving this temperature would also ensure that sealed drums have ruptured and that their VOC and water contents have largely evaporated.

With an estimated 18 days per setting to complete an ISV cycle, ISTD must be started at least five settings in front of the active melt setting. This would create a hot dried zone with an area of about 0.2 acres. This zone would be more prone to underground fires than untreated waste. Because of the transfer of heat from newly completed ISV melts to surrounding waste and soil, the waste and soil would dry out to a radius of about 4 m (12 ft) beyond the melt face (Farnsworth et al. 1999). A long string of ISV melts might create a larger dry zone than would ISTD operating immediately ahead of an ISV system. Thus, the risk of underground fire is about the same for ISV and ISTD. This risk would be managed by establishing at least 3 m (10 ft) of soil cover over the site before beginning operation of the ISTD and ISV systems. The relatively low permeability of soil at the SDA, especially after light compaction, would minimize the potential for enough air intake to support an underground fire.

Gases collected in the ISTD off-gas treatment system could be highly flammable if suddenly mixed with air because of the pyrolytic (hence, chemically reducing) conditions under which they were produced. In contrast, ISV off-gases would be diluted with very high levels of air to ensure concentrations are maintained well below lower flammability limits. High dilution of ISV off-gas with air as it exits the ground is required because the off-gas hood cannot be sufficiently sealed to the ground surface to preclude ingress of air. The ISV technology accounts for this problem by allowing very high amounts of air to pass into the hood, thereby diluting otherwise flammable gas to safe concentrations.

The low flow rate of ISTD gases would enable use of filters at each extraction point, precluding entrainment of Cs-137 and TRU particles. After HEPA filtration, gases would be cooled to remove most water along with elemental and some dissolved mercury. After removing mercury from the water, the water would be concentrated, neutralized, grouted, and pumped to a covered, lined basin for disposal. The low flow rate of highly concentrated gases would facilitate destruction of organics in a thermal oxidation unit. The acid gases resulting from thermal oxidation would be polished in a dry activated carbon filter and neutralized in a dry scrubber. Eventually, the grout basin, which would be located on the SDA, would be covered with a Modified RCRA Subtitle C Cap.

4.1.1.4 Metals and Debris Limits. The average metals content and debris content are below the defined ISV technology limits, even before considering the diluting effects of soil. Successful vitrification of melt settings containing higher levels of metals than expected at the SDA was reported for the Maralinga site in Australia (see Appendix A). The Maralinga waste included heavy steel beams. Encountering even larger metal pieces, such as vehicles, in the SDA may present a new challenge for ISV. Treatability testing or use of an alternate technology such as in situ grouting in such cases may be necessary if large metal masses are targets for ISV.

4.1.1.5 Cesium-137 (and High Ionizing Radiation) Limits. The relatively high volatility and high gamma-energy levels of Cs-137 would elevate worker risks for exposure to ionizing radiation unless Cs-137 is limited to a few curies in a setting for Traditional ISV. For Subsurface Planar ISV, a soil cover provides shielding and also may cause condensation. The shielding benefit provided by soil is an

important advantage of Subsurface Planar ISV, though condensation within the soil may somewhat diminish the effectiveness of ISV for immobilizing Cs-137. Other potential sources of ionizing radiation, including Co-60 sources and irradiated fuel materials, may contribute to unacceptable radiation levels if the melt surface becomes exposed. Additional analyses and tests to design and safely operate an ISV system for high gamma energy materials may be necessary.

4.1.1.6 Voids Limit. Waste disposed of at the SDA included $1 \times 1 \times 2$ -m ($4 \times 4 \times 7$ -ft) boxes (some constructed from steel), casks, and other large metal waste components. The presence of these wastes and the limited compacting operations conducted on wastes buried at the SDA are factors that create the potential for encountering voids of 2.5 ft³ or greater. The 2.5-ft³ limit for voids specified in Kalb et al. (1997) was based on melting experience with Traditional ISV. A combination of ISTD and Subsurface Planar ISV in the SDA application might obviate this requirement if additional design testing of the technologies, including use of the soil cover, demonstrates stable ISV operations and avoidance of MEEs. If not, injection of a grout slurry using in situ high-pressure jet grouting may be required to fill the voids. Many grouts have relatively high water contents and low permeabilities, which may cause higher and more variable rates of steam evolution during ISV processing. Also, water will drain from the grout to some extent before it sets, which would increase the risks of MEEs associated with saturated subsurface soil. The injection of the grout also would slightly increase the risks of criticality as the result of the neutron-moderating effects of water in the grout.

4.1.1.7 Load-Bearing Requirement for Surface Soils. Uncompacted waste and soil at the SDA probably would not support heavy equipment used to move off-gas hoods following completion of a melt. Design options include compaction, injection grouting, or placement of road ballast along the travel paths. Each of these options is implementable. The soil cover that complements Subsurface Planar ISV is assumed to include sufficient road ballast to support hood-moving equipment.

4.1.2 Ability to Prevent Melt Expulsion Events

Buried drums containing liquids may pressurize as they heat, suddenly releasing pressurized gases when ISV begins to melt and weaken the container. A bubble of rapidly expanding gas could rise to the surface of the melt, causing an MEE. Gas cylinders, boxes, soils, and voids containing liquids may similarly produce large quantities of vapors that result in MEEs. An explosive detonation, an explosive deflagration, and simply a large, rapid release of gas or steam are three mechanisms that may produce an MEE. Examples of these mechanisms include:

- Detonating an explosive, such as apparently occurred at the Maralinga site (see Appendix A)
- Producing a steam explosion as a consequence of molten metal or salt that suddenly envelops a container of water
- Deflagrating a mixture of high-energy combination of reducing and oxidizing agents (Dick 2001)
- Breaching an unvented gas cylinder or other pressurized sealed container within or near the glass melt
- Suddenly releasing trapped steam from relatively impermeable soil or sludge.

Key conditions for preventing MEEs in ISV applications are avoidance of (1) explosives, (2) sealed containers (including gas cylinders and bottled aqueous and organic liquids), and (3) relatively impermeable soil and sludge that may be water-saturated or hold pockets of water. These limiting

conditions were established as consequences of five large MEEs that caused equipment damage and cessation of ISV operations. Two of the MEEs were caused by pressure buildups in sealed containers, two were caused by pressure buildups in saturated soil beneath the melt, and one apparently was caused by the presence of an explosive or a gas cylinder in the waste. Melt expulsion events occurred in three of the case studies presented in Appendix A.

Explosives were probably not disposed of at the SDA, though unexploded ordnance has been found at a former bombing range at the INEEL. The disposal of nitrates and carbon-bearing waste in proximity at the SDA may create an explosive combination, as was discussed in Section 2.2.2. Nearly every drum of waste was sealed before disposal in the SDA, though many seals were ruptured during disposal operations. Bottles containing aqueous and organic liquids also were buried. Sites that shipped waste to the INEEL for disposal used gas cylinders and it is possible that some are buried in the SDA. Whether any gas cylinder was disposed of with its contents under pressure is unknown.

Applying ISV at the SDA would produce large quantities of molten metal, principally iron, because of the high steel content of the buried waste and reducing conditions that exist in most ISV melts. Smaller, but significant amounts of molten salts (mixtures of sodium and potassium nitrates with a eutectic melting point of $\sim 220^{\circ}\text{C}$) may also be produced. Molten metals and salts (to a lesser extent) could flow into voids containing standing water or other liquids. Moreover, soil at the SDA contains moisture that can be trapped and suddenly released as steam during ISV processing.

A significant fraction of the drums are likely breached as a result of the combined effects of disposal operations, rusting, internal corrosion, and the limited compaction that was performed in some areas of the SDA after the drums were buried. Previous drum-retrieval actions at the INEEL and elsewhere have shown that some drums may remain intact for decades after disposal. Some plastic and glass bottles containing liquids are probably still intact because of their high resistance to corrosion, though the small quantities of liquid they hold probably would not present a significant safety risk by comparison to the larger volumes that may exist in drums, metal boxes, and in relatively impermeable soil.

To mitigate some of the conditions that may cause an MEE, the INEEL tested an in situ method of breaching drums and bottles. This method, known as dynamic disruption, employs vibrational energy to drive rods or beams through the buried waste (Farnsworth et al. 1999). The rods or beams would be driven vertically on 2-ft centers to refusal or to the basalt layer that underlies the waste. Refusal may occur when encountering a steel plate with a thickness of 0.25 in or greater. When this occurs, another attempt to disrupt the area could be made approximately 1 ft away. In recent testing of dynamic disruption at a simulated buried waste site at the INEEL, some of the beams met refusal within the waste zone. Also, wet soil adhered to the beams extracted from the waste site following their use for dynamic disruption. Wet soil extracted from the SDA would likely be TRU-contaminated. Therefore, time-consuming contamination control measures would be required to enable reuse of the rods or beams.

Drums lying at an angle or on their sides may still hold several gallons of liquids if rod or beam penetrations occur in locations that prevent the drums from draining fully. Also, dynamic disruption would have little impact on reducing the risks associated with saturated soils immediately beneath the buried waste. Thus, despite the likelihood that dynamic disruption would breach nearly all containers, a small fraction (perhaps less than 1%) may remain intact or be capable of holding several gallons of water or other liquids. Therefore, dynamic disruption may significantly reduce the number of MEEs but probably would not altogether preclude them in a Traditional ISV application. For this reason, ISTD, Subsurface Planar ISV, and a soil cover maintained at least 3 m (10 ft) deep were assumed necessary to mitigate the potential for an MEE at the SDA.

The minimum soil cover to ensure protection of workers, the public, the environment, and the Planar ISV equipment will depend on the energy of potential explosions and the volumes and rates of potential subsurface gas releases. Dick (2001) concluded that 3 m (10 ft) of soil was marginally sufficient to protect against deflagrations involving combinations of nitrates and various carbonaceous materials known to exist in the waste. Dick (2001) did not address other energetic events, such as steam explosions, that may produce forces greater than can be mitigated by a 3-m (10-ft) soil cover.

The depth of soil cover required to contain a steam explosion depends on the quantity of water instantly vaporized, the temperature of the steam as it passes through the subsurface, and whether steam remains fully contained within molten glass or metal. Molten glass and metal are incompressible, whereas void space in soil and unmelted waste is highly compressible. If molten material does not fully envelop the steam, some of the steam will compress into and condense within the relatively porous waste and soil zone, thereby reducing its MEE potential.

The conversion of 1 gal of water to steam within molten glass would result in about 3,000 gal of steam at typical subsurface melt pressures and temperatures. By comparison, the ~20 lb of carbon used in the 55-gal deflagration tests conducted in Dick (2001) would produce as much as 14,000 gal of gas under the same pressure and temperature conditions. This implies that small, sealed containers of water that escape breaching by ISTD can be safely processed under a 3-m (10-ft) soil cover but that as little as 5 gal of water converted to steam in a steam explosion could equal conditions observed in Dick (2001).

Of greater concern are sealed drums and larger liquid volumes in breached, tilted drums that suddenly are contacted by molten metal. Dick (2001) reported that a sealed, buried drum exposed to rising temperatures to simulate an approaching ISV melt ruptured at a pressure of 38 psig. This pressure is sufficient to hold steam at about 140°C. The breaching of a drum containing heated water suddenly contacted by molten metal could cause the instantaneous release of a large amount of steam. This could result in atomizing some of the molten metal, significantly increasing its surface area for heat transfer to the steam and remaining water and facilitating the explosive release of some of the remaining liquids as steam. Hence, a steam explosion would be produced.

Clements (1982) reported that drums of Series 741 sludge contained up to 70% water, and drums of Series 743 sludge contained up to 30 gal of VOCs, primarily trichloroethane and carbon tetrachloride. If several contiguous drums of sludge deteriorated and their contents compressed into a monolithic mass, the properties of the mass may be similar to those of relatively impermeable saturated soil that have been associated with past MEEs. The instantaneous release of all steam and vapor from the equivalent of one drum of sludge because of sudden contact with molten metal or glass that flows through a subsurface channel in the buried waste also could easily exceed the conditions tested in Dick (2001). Thus, the subsurface temperature and soak time for ISTD should be sufficient to eliminate most of the water and other liquids from drums. The ISTD objective of a minimum temperature of 360°C in the buried waste and in the soil 91 cm (3 ft) below it should be sufficient to rupture nearly all of the containers and evaporate nearly all of the water and VOCs. This temperature would result in steam pressure of about 3,000 psig in a very strong container, probably ensuring that every larger-size container is ruptured.

The volume of trapped steam released from water-saturated underburden may be higher than the volume released from drums of sludge. Also, note that the Subsurface Planar ISV test on simulated INEEL sludge in a V-Tank (see Appendix A) was conducted in an unsealed vessel, which provided a pathway for steam to escape safely as it formed. Thus, the heating rods used in ISTD must penetrate well into the underburden to ensure removal of the water it contains.

The importance of precluding an MEE is illustrated by a hypothetical case in which a worker is exposed to airborne TRU contamination when an MEE causes the hood to pressurize. Assumptions used in evaluating this case include the following:

- The force of an MEE conveys a waste HEPA filter containing 1 kg of Pu-239 into the 40,000-ft³-confined volume of a hood that is normally maintained at a pressure of -0.5 in water gauge.
- Ten percent of the fine powder originally captured on the filter as air-entrained plutonium oxide particles (i.e., 100 g of Pu-239) is dispersed and entrained in the hood vapor.
- Within seconds, a second MEE occurs that pressurizes the hood, blowing 10% of the volume of the gas in the hood (4,000 ft³) into an area occupied by an unprotected worker performing maintenance on the hood. The instant evaporation and heating of approximately 11 gal of water to 1,000°C would generate sufficient gas to overcome the negative pressure of the hood and displace 10% of the volume of gas in the hood. Thus, 10 g of Pu-239 (1% of the original content of the filter) are released to the environment under this scenario.
- The 4,000 ft³ of hood gas is released near the base of the hood and immediately mixes with 100 times its volume of air, resulting in a plume of contaminated air around the hood that is 15 m (50 ft) high by 30 m (100 ft) in diameter.
- The worker breathes the contaminated air plume containing 0.000025 g Pu-239/ft³ air (10g Pu-239 in 400,000 ft³) for 0.1 minute (6 seconds) as the worker escapes the plume.

Under these conditions, the worker could receive a dose of 3,400 rem in the first year following exposure and a lifetime dose of 37,000 rem 50-year committed effective dose equivalent. The U.S. Department of Energy limits worker dose to no more than 5 rem/year. A worker who is 1,000 m (3,000 ft) downwind of the release could receive a dose of 21 rem 50-year committed effective dose equivalent when exposed to the dispersed plume over its entire passage. Though this hypothetical case involves a very improbable sequence of events, it highlights the importance of ensuring that the soil cover is not uplifted or breached even with small cracks that could allow unsafe levels of plutonium to reach the breathing zone.

Because of the high worker risk caused by an MEE that expels respirable Pu-239 into the atmosphere, workers near the hood would wear appropriate protective breathing apparatus to mitigate inhalation risks, and the hood-to-soil connection would be designed to maximize safe egress from the top of the hood in the event of a large pressurization event. Nearby RWMC workers, in general, would not be protected. They could receive large doses as noted unless evacuation alarms were employed around the facility. Investigation and cleanup following a major MEE could cause curtailment of operations for months.

Additional analysis and design tests of ISTD and Subsurface Planar ISV under conditions that bound the likely severity of MEEs at the SDA would be necessary to identify appropriate soil and road ballast cover materials over the waste. Otherwise, conditions could lead to the formation of cracks in the cover, allowing the expulsion of gas and entrained molten glass into the hood rather than venting and filtering the gas safely through the porosity of the soil. Mechanical means of maintaining an adequate depth of cover and preventing the formation of soil bridges over the melt also require testing.

4.1.3 Ability to Prevent Nuclear Criticality

Nuclear criticality is of concern when processing radioactive waste that contains high levels of fissile materials (especially Pu-239) that could become concentrated into a critical mass. The ISV and ISTD processes modify the buried waste in ways that both increase and decrease the potential for criticality. The ISV process increases the potential for criticality because of the 30 to 70% volumetric contraction of the waste that occurs during vitrification. Both the ISV and ISTD processes decrease the potential for criticality by destroying or driving off moderators such as water and plastics (Farnsworth et al. 1999). However, the pyrolyzed waste matrix may be weakened to a greater extent in ISTD because much greater volumes of waste are pyrolyzed at any given time, thereby increasing the load on waste bridges that support waste mass. This would increase the potential for settlement of the pyrolyzed waste matrix and concentration of the plutonium it contains. Compaction of the waste prior to either ISTD or ISV treatment would have the same concentrating effect.

The potential for criticality during ISV is reduced, if not eliminated, because the ISV process mixes Pu-239 throughout a melt. Relatively homogeneous conditions would be achieved in the glassy phase of the melts where most of the plutonium would be concentrated for the following reasons:

- Plutonium metal readily oxidizes in the presence of air to an oxide form that has a lower potential for criticality.
- Heat of the advancing melt front will promote oxidation of any remaining plutonium metal in the waste prior to incorporation in the melt.
- Plutonium exists at relatively low concentrations in the waste and is readily soluble in molten glass.
- The relatively high oxidation potential of the melt prevents chemical reduction of the plutonium oxide to the metallic state. Otherwise, reduced droplets of plutonium metal could settle from the molten glass and potentially concentrate into a critical mass.
- The ISV process mixes the melt. Mixing occurs because of strong, convective currents induced by high-temperature gradients within the melts during ISV processing. Mixing results in diluting waste zones containing relatively high plutonium concentrations.

Only a few drums of TRU waste at the SDA contain more than 1 kg of Pu-239, an amount that could support criticality under highly concentrated and moderated conditions. All drums investigated in a recent analysis of the potential for criticality at the RWMC were found to contain less than 2 kg of Pu-239 (Woods and Neeley 2001). The average Pu-239 content of the SDA is estimated to be about 400 nCi/gram. This equates to an average Pu-239 loading in an 11-m (35—ft) diameter by 3-m (9-ft) thick waste setting of about 16 kg. Even if each of several drums in a melt contains 1 kg of Pu-239, the total plutonium content would be below the 30 kg limit per setting established in Thompson, Bates, and Hansen (1995). Later studies have largely eliminated criticality as an issue for ISV applications at the SDA (Farnsworth et al. 1999).

4.1.4 Ability to Prevent or Control Underground Fires

Combustible materials disposed of at the SDA include paper, plastic, cloth, rubber, wood, asphalt, and flammable organic liquids (Arrenholz and Knight 1991). The combustibles content of certain buried-waste areas of the SDA may exceed 10 wt%. Combustible waste is likely to have more open porosity than soil, which also enhances its ability to burn. Potential initiators for an underground fire at the SDA include self-combustion of nitrate-soaked rags, metal powders, and filings and the high

temperatures generated by ISTD and ISV. The codisposal of significant quantities of nitrate salts in Series 745 sludge and combustible materials at the SDA would exacerbate an underground fire because of the reactivity of these materials. Underground explosions may also occur (Dick 2001).

Fire requires oxygen to support combustion. Oxygen usually is provided to underground fires by the chimney effect created by fire. The chimney effect induces a small negative pressure, which draws air toward the fire. Cutting off the source of air will extinguish most fires. Lack of oxygen and the wet condition of the waste caused by the infiltration of precipitation into the ground are normally adequate to prevent underground fires. Measures likely to be effective for preventing underground fires before, during, and after ISTD and ISV operations include the following:

- Ensuring that the waste site is fully covered with soil—including the depression created as the waste is pyrolyzed and melts during ISV that, otherwise, may expose the dried waste to air
- Installing the electrodes to a starting depth just above the buried waste to avoid exposing the dried waste to air and to minimize the potential for spreading contamination
- Capping or sealing nearby wells that are open to the waste zone.

4.1.5 Ability to Ensure Containment and Adequate Treatment of Hazardous Off-Gases

Pyrolysis rather than oxidation of the organic waste would occur during ISTD and ISV processing at the SDA because the soil cover used to prevent MEEs and underground fires would restrict the inflow of air to very low levels. The products of pyrolysis include combustible gases such as hydrogen and carbon monoxide. Other combustible gases would be produced when a cylinder of liquid acetylene or a container of gasoline ruptures, for example. A significant fraction of the combustible gases would be extracted by the off-gas system that serves the ISTD system, thereby reducing the risk and load on the ISV off-gas system.

Combustible gases would likely accumulate in an unvented off-gas hood in concentrations high enough to support a fire or explosion. Fire and explosions would be prevented in a well-designed ISV system by ensuring a sufficient flow of air through the hood at all times to dilute each flammable component of the gas to below its lower flammability limit. Curtailing power to the ISV electrodes will not stop a fire or prevent a potential explosion in the event the ventilation system is no longer functional.

Fires and explosions must be prevented to avoid the dispersion of hazardous chemicals and TRU contamination, (e.g., Pu-239) to the environment. Factors that may cause loss of function of the off-gas system include failure of equipment, human error, and natural events. Equipment failures that could cause inadequate ventilation include loss of power, mechanical malfunction of the blowers, and blinding of the HEPA filters by mists or particles. Human factors that could lead to loss of function include failure to follow safe operating procedures and poor judgment when operating under unusual conditions. Natural factors include earthquakes, tornadoes, floods, and range fires.

Design and administrative solutions are feasible for mitigating the risks associated with each of these factors and include the following examples:

- Power to multiple blowers and other key safety-related elements of the off-gas system would be provided by multiple portable generators—two blowers and generators operating simultaneously, each with a capacity of 100% of peak ventilation demand
- Redundancy in the off-gas treatment unit trains would protect against mechanical failure

- Adequate operator training would prevent most cases of operator error
- Robust design of the off-gas system would ensure function under design-basis winds and seismic conditions.

For costing purposes, a more robust ventilation system design is assumed in consideration of the following reasons:

- The history of several MEEs and fires in Traditional ISV applications
- The limited testing that has been performed to date on Subsurface Planar ISV to prove its capability to prevent MEEs
- The likelihood of high organic levels in some melt settings
- The independent moorings of the hood and the off-gas system in current ISV system designs, which increases the risk of breaking the off-gas duct between these components and losing active ventilation following a seismic event.

Features of a more robust off-gas system design may include an on-demand emergency ventilation system built on the same chassis as the hood and hardening the design of the primary and emergency off-gas systems to withstand tornadic missiles. The increased weight of the hood and off-gas systems would likely require a higher load-bearing strength of the overburden than provided by the present soil cover. For costing purposes, the 3 m (10 ft) of soil needed to protect against MEEs would consist of suitable road ballast installed using standard road construction spreaders and compactors. The hood itself would be considerably heavier than the current hood design, which can be moved to new melt settings with cranes. Additional features of the SDA hood that would add weight include automated systems to accomplish the following activities:

- Add and distribute additional overburden as the melt sinks and subsidence occurs
- Press or vibrate the overburden down to prevent bridging over the melt
- Saw off electrodes inside the hood when the melt is completed.

The hood may also be larger than the 20-m (65-ft) wide full-scale Traditional ISV hood to provide higher capacity to accommodate subsurface gas-generating events without pressurizing the hood. It is assumed the larger, heavier hood is tractor-mounted.

4.2 In Situ Vitrification Effectiveness

The overall effectiveness of ISV is comprised of two components:

- Short-term effectiveness—the ability of ISV and its supporting processes to protect workers, the public, and the environment
- Long-term effectiveness—the ability of the melt to destroy volatile and organic contaminants, immobilize radionuclides and metal contaminants, and exhibit permanence.

4.2.1 Short-Term Effectiveness

The short-term effectiveness of ISV reflects the ability of the ISV process and design to accomplish the following:

- Assure industrial and radiological protection of workers
- Control emissions of hazardous chemicals and radionuclides to safe levels that comply with applicable or relevant and appropriate requirements and protect human health and the environment.

Worker hazards include exposure to ionizing radiation, inhalation of airborne contamination, and exposure to mechanical, electrical, and thermal hazards.

Workers would be exposed to ionizing radiation if significant volatility of Cs-137 occurs and the soil cover is not sufficient when vitrifying Cs-137 sources or irradiated fuel materials. These conditions may increase the concentrations of Cs-137 in the hood and off-gas treatment system to unsafe levels. Significant worker exposures could occur if radioactive sources or irradiated fuel materials are expelled into the hood confinement in an MEE. A soil cover 3 m (10 ft) thick or more would likely preclude MEEs and would condense and filter most of the volatile Cs-137. Additional evaluation is required to establish the thickness of soil.

Workers would be exposed to inhalation hazards in an MEE when primary and emergency ventilation is lost and when conducting maintenance, such as changing HEPA filters. The use of appropriate personal protective equipment and training would be effective in mitigating these hazards. Workers would be exposed to significant mechanical hazards because of the need to frequently move electrodes, hoods, and off-gas systems. Workers would be exposed to electrical and thermal hazards because of the need to conduct maintenance on top of and at the base of hoods and on thermally hot components of the off-gas system. Training, remote design enhancements, and design tests to establish safe operating boundaries would be effective in managing mechanical, electrical, and thermal hazards.

Emissions from the off-gas systems must be controlled to protect the workers, public, and environment. The wide range and uncertainties in contaminants and waste types at the SDA pose challenges to the off-gas treatment system design. The list of contaminants present at the SDA is extensive and complex. Most of the inorganic contaminants at the SDA would be immobilized in the melt, and a small fraction would migrate into the soil. The use of a soil cover when melting would reduce particle emissions through the processes of filtration and condensation. Volatile contaminants, including volatile products of pyrolysis, would be drawn into the off-gas systems where they would be treated.

The fate of contaminants of potential concern during ISV was evaluated in the *ISV Treatability Study Work Plan* (Farnsworth et al. 1999). The level of conservatism in the off-gas treatment designs would depend on reducing uncertainty in the estimated concentrations of off-gases. The feasibility of and need for treating the contaminants of potential concern depends on their projected concentrations and quantities released over time and on the regulatory standards that limit emissions.

The ISTD and ISV off-gas treatment systems would generate secondary waste. Secondary waste may include failed and corroded equipment, spent activated carbon, spent dry scrubber media, wet scrubber solutions and sludge, and mercury concentrates. Spent carbon and dry scrubber media are assumed to be acceptable for onsite disposal without further treatment. Sludge and solutions would be neutralized and grouted to immobilize heavy metals and radionuclides. Mercury waste would be amalgamated. All treated secondary waste is assumed acceptable for disposal.

4.2.2 Long-Term Effectiveness

The Environmental Protection Agency's *Technology Screening Guide to Radioactively Contaminated Sites* (EPA 1996) states in regard to the ISV product, "The vitrified mass is very resilient to weathering, which makes it effective for long-term containment of waste." Every full-scale melt tested to date has met TCLP and PCT leach-resistance requirements, though additional tests may be required to evaluate the effects of leaching in the presence of glass alteration phases and leachates that are in equilibrium with those phases (see Section 2.1.5).

The quality of the melt depends on the character of the waste, particularly the content of silica relative to the content of flux, including alkalis such as sodium and potassium (Pegg 1996). High concentrations of alkalis significantly reduce the weathering- or leach-resistance of the vitrified mass. The concentration of alkalis in SDA melts is expected to be within the acceptable 1.4 to 15% range defined in Kalb et al. (1997). However, a few melt settings could contain an unusually high number of Series 745 sludge drums, which contain nitrates of sodium and potassium. Low electrical resistivities in the glass during melting are indicative of high alkali levels. Adding a high-silica material (such as silica sand or soil) to the top of the melt and allowing the mixing action created in the melt to mix and vitrify the added silica would likely correct the problem. Tests involving the highest expected levels of Series 745 sludge drums may be required to verify the effectiveness of this technique and the resulting vitrified product.

Some chemicals, possibly small amounts of iron, would be reduced to their metallic states and sink to a molten metal zone at the bottom of the melt (Buel et al. 1987). Waste already in metallic states, such as steel pipe, aluminum heat exchangers, and probably beryllium ingots, would melt, sink to the bottom of the melt, and accumulate with any metals formed by chemical reduction. Alloying chemicals and activation products such as C-14 within the waste metals likely would remain largely in the metals after melting because of the reducing conditions that would exist in the glass. Some of the metallic lead in the waste may dissolve in the glassy phase, and some may melt and settle to a pool below the predominantly iron pool. The oxidation potentials of uranium and plutonium are sufficiently high that they would be resistant to reduction and, thus, would be incorporated within the glassy phase of the melt (Farnsworth et al. 1999). Americium also should remain within the glassy phase of the melt (McGlinn et al. 1998). The metallic zone of an ISV melt may be subject to TCLP testing for RCRA metals. A TCLP evaluation of the metals created during ISV treatability testing appears necessary to verify the long-term effectiveness of the metal zone.

Some fraction of dissolved nitrate salts may wick into the pores of the underburden and sidewall soils. Alkali salts, which are highly soluble in water, may entrain other alkalis as they migrate, such as Cs-137 and dissolved heavy metals. The salt zone, if created, also may be subject to TCLP testing. A TCLP evaluation of any salt zone created during ISV treatability testing appears necessary to verify the long-term effectiveness of the zone, if created.

Organic contaminants would be pyrolyzed or evaporated, and the volatile components largely driven from the melt zone into the off-gas systems. There would be some potential for VOCs with low boiling points to volatilize ahead of the 100°C isotherm, where water in the waste and soil is evaporating, and to condense in cooler adjacent soil. However, in the unlikely event it is needed, soil vapor extraction could be used after ISTD and ISV processing to recover volatile chemicals originating in the melt zone.

Semivolatile species, such as Cs-137, lead, mercury, and cadmium would evaporate to some extent and condense in the space between the 100°C isotherm and the melt, including the soil cover over the melt. Subsurface Planar ISV tests involving the highest expected levels of semivolatile species of concern in a melt appears necessary to assess the need for additional treatment of adjacent soil. If necessary, in situ grouting would likely be effective in immobilizing certain heavy metals in the cover and soil along the sides of the melts. In situ grouting would be difficult to implement beneath the melt.

5. SUMMARY OF DATA GAPS FOR IN SITU VITRIFICATION

Major uncertainties in the application of ISV to waste buried at the SDA include the following:

- Ability to successfully implement the relatively unproven technologies—Subsurface Planar ISV—and its key supporting technology, ISTD, including associated off-gas and secondary waste treatment technologies
- Ability to preclude MEEs, fires, and explosions that compromise safety and the function of the primary off-gas treatment system
- Ability of metal pools at the base of the melt to provide long-term effectiveness.

Table 2. Potential in situ vitrification data gaps and evaluations.

Potential Data Gap	Evaluation and Recommendation
Can variability in waste compositions and physical properties be defined sufficiently to form an adequate safety basis for designing the ISV off-gas system required to prevent fires in the hood when encountering high concentrations of combustibles and containers of flammable organic liquids?	Yes. Variability is not significant when soil composition is included. Define bounding waste and disposal site conditions and evaluate with design tests using simulated waste.
Can Subsurface Planar ISV be operated in a manner that precludes MEEs under all bounding conditions without first preconditioning with ISTD?	Yes. A soil cover can be added to address MEEs. Conduct Subsurface Planar ISV design tests using simulated waste to evaluate bounding conditions.
If ISV alone cannot preclude MEEs, can ISTD pretreatment effectively mitigate liquids in sealed containers and evaporate water in the underburden?	Possibly. Conduct integrated ISV and ISTD design tests using simulated waste to evaluate bounding conditions.
Can permeability and moisture levels of underburden soil and gas-release characteristics following ISTD be determined with sufficient certainty to define the thickness of overburden required to prevent MEEs?	Yes. Evaluate existing data on underburden soils and subsurface topography, obtain additional samples, and analyze for water content, hydraulic conductivity, and potential for rapid steam generation.
Can overburden of the required thickness be maintained and not become incorporated in the melt?	Yes. Evaluate overburden consumption and methods of maintaining required thickness as part of design tests.
Can Cs-137 and Co-60 sources and irradiated fuel materials be safely processed?	Yes. Evaluate waste generation and disposal records, and calculate dose rates for an MEE expulsion of the bounding source or irradiated fuel materials into the confinement area of an unshielded hood.
Can zones containing large quantities of Series 745 sludge with its high alkali content be vitrified and yield high quality melts?	Yes. Evaluate waste generation and disposal records to establish bounding conditions, and conduct an ISV design test using simulated Series 745 sludge and other waste to assess requirements for adding silica to the melt to achieve performance objectives.
Can large metal objects, such as vehicles, be successfully treated?	Possibly. Evaluate waste generation and disposal records to establish bounding conditions, and either conduct an ISV design test using simulated metal waste or define an alternative technology for large metal objects.
Will the area of elevated temperature immediately	Possibly. Evaluate waste generation and disposal

Table 2. (continued).

Potential Data Gap	Evaluation and Recommendation
surrounding the melt zone be prone to underground fires, especially when augmented with potential exothermic reactions involving nitrates?	records to establish bounding conditions. If necessary, conduct an integrated ISV and ISTD test using simulated Series 745 sludge, combustibles and other waste to evaluate bounding conditions.
Will lead and other toxic heavy metals and radionuclides accumulate in the metal zone in unacceptable concentrations?	Possibly. Evaluate waste generation and disposal records to establish bounding conditions, and evaluate fate of heavy metals and radionuclides in design tests.
Will semivolatile chemicals and radionuclides be mobilized and condense outside the melt zone in unacceptable quantities?	Possibly. Evaluate waste generation and disposal records to establish bounding conditions, and evaluate fate of semivolatiles in design tests. If the surface barrier may not be effective in mitigating the risks associated with condensed semivolatiles, sample the test soils containing high levels of condensates, and if necessary, grout the samples and test leach-resistance of grouted soil.
Will unacceptable quantities of volatile organic chemicals be mobilized and condense outside the melt zone rather than being channeled upward into the off-gas system?	Possibly. Evaluate waste generation and disposal records to establish bounding conditions, and assess fate of volatiles in design tests and contaminant mobility analyses.

6. REFERENCES

- American Geological Institute, 1983, *Dictionary of Geological Terms*, Bates, R. L. and J. A. Jackson, Editors, 3rd Edition, Anchor Books, Doubleday.
- ARPANSA, 1998, *Maralinga Rehabilitation Project Gallery: Part 2 1998*, <http://www.arpansa.gov.au/>, Australian Radiation Protection and Nuclear Safety Agency, Sydney, Australia.
- Arrenholz, D. A. and J. L. Knight, 1991, *A Brief Analysis And Description of Transuranic Wastes in the Subsurface Disposal Area of the Radioactive Waste Management Complex at INEL*, EGG-WTD-9438, Idaho National Engineering Laboratory, Idaho Falls, Idaho.
- ASTM C 1285-97, 1997, *Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses: The Product Consistency Test (PCT)*, American Society for Testing and Materials.
- Becker, B. H., J. D. Burgess, K. J. Holdren, D. K. Jorgensen, S. O. Magnuson, and A. J. Sondrup, 1998, *Interim Risk Assessment and Contaminant Screening for the Waste Area Group 7 Remedial Investigation*, DOE/ID-10569, Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.
- Borschmann, G., 2000, *Maralinga: The Fall Out Continues*, Radio National's Weekly Investigative Documentary, www.abc.net.au/rn/talks/bbing/stories/s120383.htm, web page visited Sunday, April 4, 2000.
- Buelt, J. L., C. L. Timmerman, K. H. Oma, V. F. Fitzpatrick, and J. G. Carter, 1987, *In Situ Vitrification of Transuranic Wastes: An Updated Systems Evaluation and Applications Assessment*, PNL-4800 Suppl. 1, Pacific National Laboratory, Hanford, Washington.
- Callow, R. A., L. E. Thompson, J. R. Weidner, C. A. Loehr, B. P. McGrail, and S. O. Bates, 1991, *In Situ Vitrification Application to Buried Waste: Final Report of Intermediate Field Tests at Idaho National Engineering Laboratory*, EGG-WTD-9807, Idaho National Engineering Laboratory, Idaho Falls, Idaho.
- Clements, Jr., T. L., 1982, *Contact Code Assessments for INEL Contact-Handled Transuranic Wastes*, WM-F1-82-021, Idaho National Engineering Laboratory, Idaho Falls, Idaho.
- Dick, John R., 2001, *Nitrate Explosive Tests to Support the Operable Unit 7-13/14 In Situ Vitrification Project*, INEEL/EXT-01-00265, Rev. 0., Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.
- Dietz, R. N., R. F. Wieser, R. W. Fajer, J. D. Mancini, and G. I. Senum, 1996, *In-Situ Vitrification (ISV) Organic Surrogate Vapor Emissions During a 1-Ton Pilot Melt*, BNL-63981, Brookhaven National Laboratory, Upton, New York.
- DOE/EM, 1997, "In Situ Vitrification Fact Sheet," www.bechteljacobs.com/emef/newfacts/facts/insituvit.html, Department of Energy and the Environmental Management Program, March 7, 2001.
- Dragun, J., 1991, "Geochemistry and Soil Chemistry Reactions Occurring During In Situ Vitrification," *Journal of Hazardous Materials*, Vol. 26, pp. 343-364.

- EPA, 1996, *Technology Screening Guide for Radioactively Contaminated Site*, Office of Air and Radiation Office of Solid Waste and Emergency Response, Environmental Protection Agency 402-R-96-017, Washington, DC, 20460.
- Farnsworth, R. K., D. J. Henrikson, R. A. Hyde, D. K. Jorgensen, J. K. McDonald, D. F. Nickelson, M. C. Pfeifer, P. A. Sloan, and J. R. Weidner, 1999, *Operable Unit 7-13/14 In Situ Vittrification Treatability Study Work Plan*, DOE/ID-10667, U. S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.
- Fuhrmann, M., H. Zhou, and M. A. Schoonen, 1996, *In-Situ Vittrification: Leachability and Elemental Tracer Study*, Brookhaven National Laboratory, Upton New York.
- Geosafe, 1999, Cold Demonstration of Nontraditional In Situ Vittrification at the Los Alamos National Laboratory, GSC-363, ECCP-11, Geosafe Corporation, Richland, Washington.
- INEEL, 1998, *Monitoring and Verification of Tank In Situ Vittrification*, INEEL-LD-98-189, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.
- Kalb, P. D., J. R. Conner, J. L. Mayberry, B. R. Patel, J. M. Perez, and R. L. Treat, 1997, *Innovative Site Remediation Technology, Design and Application, Stabilization/Solidification*, American Academy of Environmental Engineers.
- LANL, 2000, *Site Technology Demonstration - NTISV: Performance/Success*, www-emtd.lanl.gov/SubCon/Performance.html, web site visited December 27, 2000.
- Lindgren, E. and J. Phelan, 2000, *Remediation of Inorganic Contamination in the Vadose Zone in Vadose Zone Science and Technology Solutions*, Looney, B. B. and R. W. Falta, Editors, Battelle Press, Richland, Washington, Vol. II:1239-1307.
- LMITCO, 1996, *Technical Evaluation Summary of the In Situ Vittrification Melt Expulsion at the Oak Ridge National Laboratory on April 21, 1996, Oak Ridge, Tennessee*, ORNL/ER-374/R1, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- LMITCO, 1997, *In Situ Vittrification Demonstration at Pit 1, Oak Ridge National Laboratory - Volume 1. Results of Treatability Study*, ORNL/ER-425/V1, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- LMITCO, 1998, *Treatability Study for Planar In Situ Vittrification of INEEL Test Area North V-Tanks*, INEEL/EXT-98-00854, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.
- Mayne, P. W., S. E. Burns, and L. J. Circeo, 2000, "Plasma Magmavication of Soils by Nontransferred Arc," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126(5):387-396.
- McGlinn, P. J., K. P. Hart, J. R. Harries, J. A. Weir, and L. E. Thompson, 1998, *Scientific Studies on the Immobilization of Pu by ISV in Field Trials at Maralinga, Australia*, Material Research Society Symposium Procedure, Materials Research Society. Vol. 506: 239-247.
- McGrail, B. P., D. H. Bacon, W. L. Ebert, and K. P. Saripalli, 2000, *A Strategy to Conduct an Analysis of the Long-Term Performance of Low-Activity Waste Glass in a Shallow Subsurface Disposal System At Hanford*, PNNL-11834 Rev.1, Pacific Northwest National Laboratory, Richland, Washington.

- NRC, 1996, "Glass as a Waste Form and Vitrification Technology: Summary of an International Workshop," Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources, National Research Council, National Academy Press, Washington D.C.
- Pegg, I. L., 1996, Basic Considerations in the Application of Vitrification Technologies, *Stabilization and Solidification of Hazardous, Radioactive and Mixed Wastes*, Vol. 3. in ASTM STP1240, Gilliam M. and C. C. Wiles, Eds. American Society for Testing and Materials.
- Thompson, L. E., S. O. Bates, and J. E. Hansen, 1995, *International Applications Status of In Situ Vitrification on Mixed TRU and LLW Buried Wastes*, Proceedings of the Third Biennial Mixed Waste Symposium, Baltimore, Maryland.
- Thompson, L., G. Huddleston, J. Jones, M. Springer, D. Reichart, and B. Campbell, 2001, *Results From the Non-Traditional (Sub-Surface) In Situ Vitrification Demonstration for Mixed Waste Applications at the Los Alamos National Laboratory*, Proceedings of the Symposium on Waste Management 2001, Tucson, Arizona.
- Woods, K. B. and M. N. Neeley, 2001, *Criticality Safety Evaluation for Overloaded Drums at RWMC*, INEL/INT-97-00695 Rev. 1, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.

Appendix A
Detailed in Situ Vitrification Case Studies

Appendix A

Detailed In Situ Vitrification Case Studies

A1. OAK RIDGE NATIONAL LABORATORY, WASTE AREA GROUP 7, PIT 1 DEMONSTRATION MELT

In April 1996, a seepage pit (Pit 1) formerly used for the disposal of radioactive liquid waste was selected for demonstrating Traditional ISV at the Oak Ridge National Laboratory. Pit 1 was one of a series of pits that had been constructed between 1951 and 1966 on the peaks of ridges to facilitate seepage of liquids. In situ vitrification was the technology planned for remediating these pits.

Pit 1 had been operated as a seepage pond to collect fine-grained sediments. In 1981, this pit was backfilled with native clean soil consisting of greater than 50% clay-sized materials and then covered with an asphalt cap to prevent infiltration of precipitation.^g The groundwater level was within 3 m (10 ft) of the surface (DOE/EM 1997). The pit extended 7–8 m (24–26 ft) below ground surface so the upper 2 m (6 ft) of clean soil and asphalt was removed in order to maximize the effectiveness of the melt.^a Before the melt began, the level of the water table ranged up to 3 m (10 ft) above the eventual bottom of the molten mass outside of the 100°C isotherm (LMITCO 1996).

This experimental melt was performed with a Traditional ISV configuration designed by Oak Ridge National Laboratory to experiment with systems that had not been previously used.^h The ISV demonstration ran for 17 days, achieving a melt depth of approximately 6 m (20 ft) before experiencing an upheaval of steam and molten glass known as an MEE. Figure A-1 shows a schematic of the calculated melt body size at the time of the MEE. The off-gas hood and associated equipment caught fire and expelled glass particles and uncontrolled off-gas. Approximately 9.58E-08 Ci of Cs-137 were released in this event. This release could result in a hypothetical dose impact to the maximally exposed individual of the general public of 0.015 μ rem (compared to U.S. Department of Energy limit of 10 mrem/year) (LMITCO 1997). No one was injured or exposed to contamination, and no contamination was detected in any ambient air monitors or samplers possibly because they were not positioned for optimal interception of any escaping off-gas plume. Repairs to the hood, several control panels, window viewpoints, material addition system pneumatic lines and controls, roughing filter equipment, and miscellaneous cables, wiring, and equipment were estimated to cost approximately \$500,000.

After a thorough investigation, the MEE was reported to have been caused by “steam pressurization at some depth beneath the molten body in excess of the static hydraulic pressure of the molten body ...” (LMITCO 1996). The MEE likely occurred because the melt expanded into impermeable shale as it progressed. This sealed-off the gas escape route for trapped water vapor, forcing expanding vapor up through the melt.

g. B.P. Spalding, Oak Ridge National Laboratory, Telephone communication with Tami Thomas, CH2M Hill, January 4, 2001.

h. J. Hansen, AMEC GeoMelt, Telephone communication with Tami Thomas, CH2M Hill, January 12, 2001.

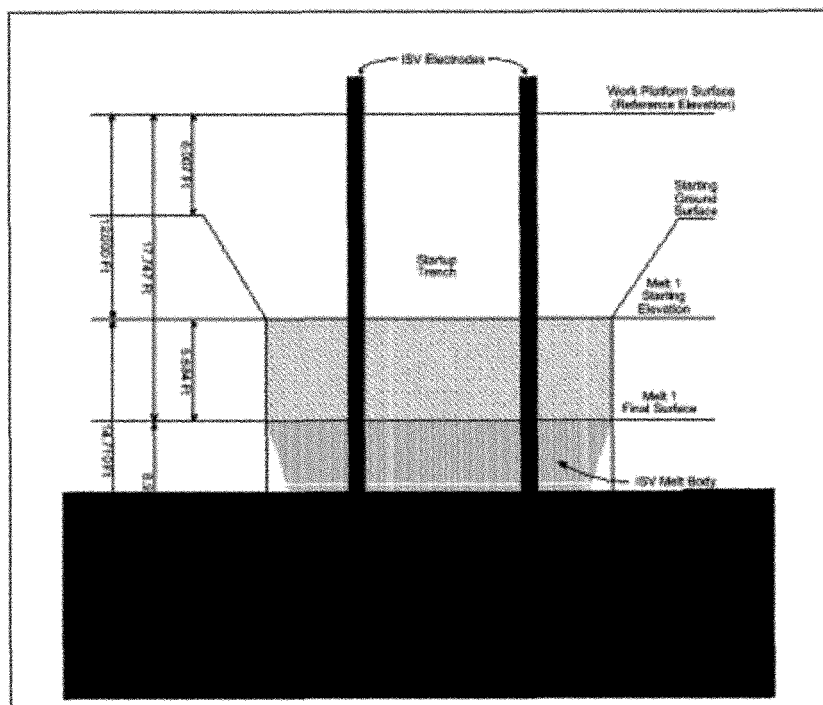


Figure A-1. Cross-section of calculated melt size at time of melt expulsion event at Oak Ridge National Laboratory (adapted from graphic from Lockheed Martin [LMITCO 1996]).

Numerous recommendations for improving the ISV design and operation arose from the evaluation of this event (LMITCO 1996), including the following:

- Draw down perched groundwater to well below the final depth of the melt body
- Provide vent pipes beneath or at the final melt body depth with a system for monitoring their effectiveness
- Devise a technique to monitor gas pressure beneath the melt in real time to allow operational prevention of an MEE
- Maintain the electrodes some distance above the impermeable contact to slow steam generation and potentially prevent an MEE.

These recommendations may not be appropriate for ISV at the INEEL SDA because the conditions differ, the hood has been redesigned, and new process configurations (i.e., Subsurface Planar ISV) would be deployed.ⁱ Specifically, the SDA is generally less water-saturated in the waste zone than waste sites at Oak Ridge National Laboratory although there is a potential for saturated clay underburden just above the basalt in the SDA.

The fine-grained nature of the native soil and the presence of a natural subsurface barrier are shared characteristics. Unlike the weathered, sedimentary rock barrier at Oak Ridge National Laboratory, the

i. J. Hansen, AMEC GeoMelt, Telephone communication with Tami Thomas, CH2M Hill, January 12, 2001.

basalt surface at the SDA may be highly irregular, which could aid in allowing moisture to move away from the melt.^j However, this irregularity has not been confirmed and may constitute a data gap for the site.

The Subsurface Planar ISV planned for the now-cancelled SDA cold test would have minimized the size of the footprint of a single melt, reducing the potential for vapor to be trapped beneath the melt zone until the planar melts grow together. Additionally, the melts at the SDA would be started and maintained with a minimum overburden of 3 m (10 ft) of soil over the melt. The soil cover would provide confinement of the melt and prevent the molten glass from spurting onto the hood or other equipment.

A2. GENERAL ELECTRIC APPARATUS SHOP POLYCHLORINATED BIPHENYL REMEDIATION

Traditional ISV was successfully used at the General Electric Apparatus Shop, a commercial site in Spokane, Washington, for remediating PCB-contaminated soil. The materials melted included dry, gravelly sand and waste debris; which were partially staged in prepared pits.

The first five melts were performed in 1994 to demonstrate the technology in support of obtaining a Toxic Substances Control Act permit required for PCB treatment. Debris, consisting of drums, concrete, and asphalt, was buried at the bottom of the staged pits. A final three or four melts were performed in 1996 under the Record of Decision for remediating the site. Final melt depths were approximately 5 m (16 ft) with each melt taking approximately 10 days. The technology worked well in a confined location in the middle of the city, and there were no complaints from the public.^k

In spite of the relative proximity of this site to the SDA, more differences in the geologies than similarities exist between these sites. For example, the sandy aquifer material at the Spokane site is much coarser than the lake-bed deposits at the SDA, and the moisture conditions of the dry Spokane material and the potentially saturated underburden beneath the waste at the SDA are significantly different. Additionally, the waste material at the Spokane site was predominately composed of sediments, rather than predominantly highly variable processing wastes at the SDA.

A3. IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY V-TANK MELT DEMONSTRATION OF PLANAR IN SITU VITRIFICATION

In April 1998, the INEEL conducted a nonradioactive demonstration of Subsurface Planar ISV for remediating simulated V-Tanks at the Tank Area North. Materials in the tanks consist of PCB-contaminated sediments; the soil surrounding the tanks is contaminated with radioactive cesium, TRUs, and other radionuclides (INEEL 1998).

A tank 4 m (12 ft) long by 2 m (8 ft) in diameter was buried 3 m (10 ft) below ground surface and filled with layers of soil and nonradioactive cesium to simulate V-Tank sludge. The remaining void volume of the tank was then filled with additional soil. The tank was vented along its length with a series of five, 36-cm- (14-in.-) diameter vertical pipes containing a natural zeolite chosen for its high filtering capacity. The vertical pipes vented directly into the off-gas hood. Two parallel Subsurface Planar ISV

j. R. K., Farnsworth, INEEL, Telephone communication with Tami Thomas, CH2M HILL, February 14, 2001.

k. G. Gregory, INEEL, Telephone communication with Tami Thomas, CH2M HILL, January 4, 2001.

melts were started on opposite sides of the tank at 3 m (10 ft) below ground surface and melted downward from that depth. As the two parallel melts grew together, steam generated from within the tank was vented through the zeolite to the surface, and the tank was subsequently melted (along with its contents).

A 195-metric-ton melt was created, measuring 6 m wide (20 ft) by 9 m (28 ft) long by 2 m (5 ft) high at the center and 1.1–1.2 m (3–4 ft) thick at the edges. The center of the melt subsided 4 m (14 ft). The depth of the melt extended from 3 m (10 ft) to 6 m (19 ft) below ground surface. Figure A-2 shows a schematic of the tank melt configuration.

The tank melt was performed without incident. Pressure sensors in the bottom of the tank were used to indicate the pressure head of the water. This pressure generally dropped over the test period as the water evaporated from the tank. At no time did the pressure transducers indicate a buildup of pressure in the tank as it was processed. No indication of cesium migration was found.^l This finding is consistent with the observation that the temperature of the vent lines did not exceed 100°C as the result of the generation of steam throughout the test and that the vent lines apparently did not fully subside with the melt. Thus, any cesium that reached temperatures high enough to volatilize likely condensed within the dry soil layer between the 100°C isotherm and the hot melt surface. Samples of soil near the melt surface were apparently not taken and analyzed to enable assessment of this hypothesis. Nevertheless, the fraction of cesium in the waste that reached the off-gas system was very low, highlighting the potential of the soil layer over the melt to condense any volatilized cesium and other hazardous components. The operational stability of the test also highlighted the importance of ensuring that containers holding water or other liquids are vented and that sufficient time is provided to evaporate liquids before they are exposed to molten glass (or metal).

A4. MARALINGA TEST RANGE IN SITU VITRIFICATION REMEDIAION PROJECT

From October 1998 through March 1999, full-scale ISV remediation was performed on buried waste contaminated with plutonium at the Maralinga Test Range in Taranaki, Australia (Mc Glinn et al. 1998). The British used the Maralinga Test Range in the 1950s and 1960s for aboveground testing of nuclear weapons. The ISV site consisted of 11 pits that had been blasted 3–4 m (9–13 ft) into the native limestone rock and then filled with material contaminated from the nuclear weapons tests.

The waste was highly variable, consisting of steel debris, instruments, bricks, clothing, drums, cables, and other wastes, with an indeterminate amount of soil. The primary component of the waste was very thick structural steel beams and other scrap metals (37 wt%). The waste was contaminated with plutonium, lead, beryllium, barium, and other chemicals.^m

Thirteen Traditional ISV melts were performed on the pits. To increase the melting point and glass-making quality of limestone, 2–3 m (8–10 ft) of sand was placed on top of the pits. The sand enabled processing temperatures of up to 1,500°C, assuring high-quality glass.

l. R. K., Farnsworth, INEEL, Telephone communication with Tami Thomas, CH2M HILL, February 14, 2001.

m. L. Thompson, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, January 9, 2001.

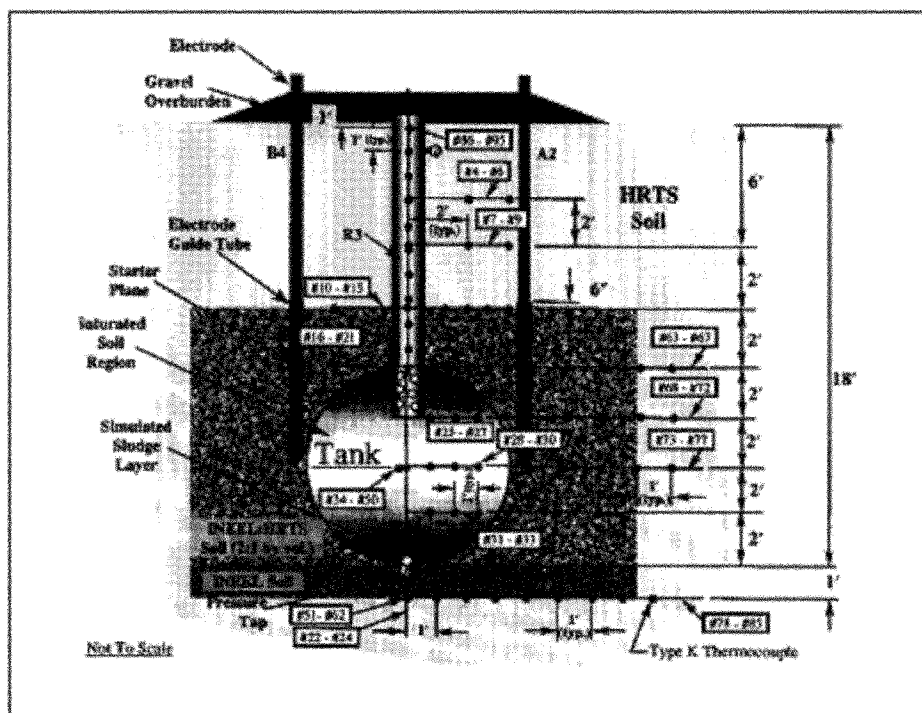


Figure A-2. Schematic of V-Tank demonstration melt configuration (graphic from Lockheed Martin [LMITCO 1998]).

Because of the low melting temperature of the surrounding native limestone, a trench was dug around the perimeter of each melt and backfilled with refractory sand. This was needed to control the lateral growth of the melt. Excessively wide and probably shallow melts could have been created without such measures.ⁿ The ISV melt began at the top of the sand. As the melt progressed, the melted waste was blended with the melted sand by convective currents. The final melt quality was excellent, easily passing PCT.^o Figure A-3 presents a photograph of the off-gas hood frame and equipment used at Maralinga.

Thirteen melts had been accomplished by March 1999 when an explosion shut down processing. The ISV contractor performed an investigation and concluded that the cause of the explosion was buried explosives or a buried gas cylinder. The project was discontinued.

Like the SDA site, the Maralinga site contained waste that was highly variable in nature, consisting of drums and other waste buried in pits. The presence of a rock barrier at the bottom of the pits is also similar to the basalt layer below the SDA. Conversely, waste in the SDA probably contains more soil (estimated at 52%) and less metal on average than that at Maralinga though individual melt settings at the SDA may contain similar levels. Another difference is the type of rock and soil in which the pits were dug—the soil at the INEEL has much better glass-forming characteristics than the limestone at Maralinga, which required the addition of sand to produce a high-quality glass. The groundwater at the Maralinga site is very deep and well below the level that could affect ISV operations. Though surface flooding is a common problem at Maralinga, it did not impact ISV operations.^s

n. J. Hansen, AMEC GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, January 12, 2001.

o. L. Thompson, AMEC-GeoMelt, Telephone communication with Tami Thomas, CH2M HILL, January 9, 2001.

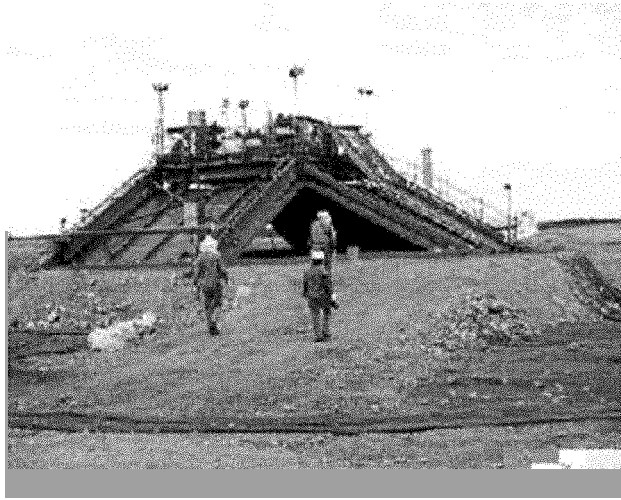


Figure A-3. Maralinga in situ vitrification apparatus (photo from ARPANSA 1998).

A5. LOS ALAMOS NATIONAL LABORATORY FIELD-SCALE COLD AND HOT TESTS OF SUBSURFACE PLANAR IN SITU VITRIFICATION

Subsurface Planar ISV tests were completed in April 2000 at Los Alamos National Laboratory. Two tests, a cold test with simulated wastes and a hot test with actual contaminated wastes, were performed. Both tests were conducted on underground adsorption beds (one simulated and one actual) for treating liquid effluent from nuclear laundry and research operations. The beds consisted of a layer of dry cobbles 10–61 cm (4–24 in. diameter) over layers of gravel and sand placed on top of native tuff. The actual adsorption beds were constructed in pits, approximately 6 m (20 ft) wide, 9 m (30 ft) long, and 2 m (6 ft) deep, and subsequently backfilled with layers of sand and gravel.

Water slightly contaminated with radionuclides from laundry and research activities had been trickled through the actual bed to adsorb and filter contaminants. Contaminants at the site include americium, plutonium (up to 525 pCi), uranium, strontium, cesium, and tritium. The contamination extended to approximately 7 m (22 ft) below ground surface (Geosafe 1999). Over the years, the voids in the cobble and gravel zones filled with silt.

The cold test was performed in a simulated pit that closely resembled the actual pit except that it occupied a smaller area and lacked the presence of radioactive contamination. Dynamic disruption was used to break up the native tuff below the cobble layer. This pretreatment was intended to prevent the formation of vertical walls of tuff adjacent to the melt that could slough off and fall into the subsided melt.

The starter paths were injected in two 1-m (3-ft) high planes from 2 to 3 m (7 to 10 ft) below ground surface by drilling a series of injection borings horizontally spaced approximately 30 cm (12 in.) apart to the desired depth. Consequently, the melts began below the base of the adsorption bed materials. The cold test was conducted during an 8-day period in April 1999 without incident, incorporating nearly the entire overburden depth into the melt as intended. Nonradioactive tracers that had been added to the cold test pit were found well dispersed in the melt, and the leach resistance of the melt product was excellent.

The hot test was conducted during a 2-week period in April 2000. During processing of the actual waste, a condition known as a cold cap formed at the surface. A cold cap consists of a layer of formerly or partially molten soil that has cooled at the surface enough to harden and bridge over the molten material while the molten material continues to subside. This creates a void between the cap and the molten mass. A void is undesirable since it may accumulate flammable gases or compromise the ability to maintain soil of a minimum thickness over the melt to protect against MEEs. The hot test was suspended while the cap was broken up. Aside from this setback, the melt progressed without incident (Geosafe 1999). Following completion of melting operations, the hot-test equipment was found to be free of detectable contamination.

Tentatively, the radioactive melt was planned to be cored in August 2002 after it had cooled to close to ambient temperatures. In October 2000, thermocouple readings at the site had already fallen to approximately 370°C. Soil that surrounds the radioactive melt has been sampled and analyzed, but the results have not been published.

Though the processed material at Los Alamos National Laboratory differs from that at the SDA in moisture, grain size, and waste composition, the native tuff below the excavated cobble layer at Los Alamos National Laboratory presented a condition similar to that of the basalt barrier below the waste at the SDA.

One of the potential benefits of Subsurface Planar ISV was the achievement of a final melt depth of more than 8 m (25 ft). Greater depths are believed achievable. Notably, the melts were terminated, not because the technical limits of the technology had been reached but because the remedial action objectives for the project had been achieved. The lack of detectable contamination on the equipment was a key finding that highlights the benefit of the cap in filtering and minimizing airborne contamination.

A6. BROOKHAVEN NATIONAL LABORATORY IN SITU VITRIFICATION TRACER AND VAPOR EMISSIONS STUDY

A small-scale field test of Traditional ISV was conducted in June 1996 at Brookhaven National Laboratory to simulate ISV treatment of the Glass Pits site thereby providing information to support selection of methods for remediating the site (Dietz et al. 1996; Fuhrmann et al. 1996). A test pit was dug to a depth of about 1 m (3 ft) and was filled with bottles, broken glass, crushed metal cans, plastic containers, and tracers at different levels of the pit for evaluating the fate of VOCs and key radionuclides. The organic tracers included acetone and perfluorocarbon; the surrogate radionuclides included cesium chloride, strontium nitrate, rubidium nitrate, and neodymium oxide.

Following vitrification and a period of cooling, the glass monolith and surrounding soil was sampled. Analysis showed that 0.5% of the sodium, 1.7% of the cesium, and 2.8% of the rubidium migrated from the pit by vapor-phase transport and condensed in the soil. The remaining waste components and surrogate radionuclides were well mixed within the glass matrix with the exception of iron, which was present as 1-mm, metallic spheres. Accelerated leach tests indicated very low leach rates for the first 10 days of leaching followed by increasing leach rates. Analysis of off-gas collected in the hood revealed that more than 85% of the acetone evaporated without reacting; somewhat lower evaporation levels were observed for the perfluorocarbon tracer. Analysis of soil vapor showed the lower the elevation of released organic tracer, the higher its concentration in the soil gas below the melt.

Though this was a small-scale test, the results indicate the potential for VOCs to evaporate without destruction and for cesium and other semivolatile materials to condense to some extent in the soil that surrounds larger melts.

A7. IDAHO NATIONAL ENGINEERING LABORATORY INTERMEDIATE IN SITU VITRIFICATION FIELD TESTS

Two ISV field tests were conducted on simulated buried waste during June and July 1990 at the Idaho National Engineering Laboratory to assess the general suitability of the process for remediating buried waste found at the Idaho National Engineering Laboratory (Callow et al. 1991). Two test pits were prepared. The first simulated typical SDA waste disposed in boxes and drums in a random array; the second simulated a stacked array. The first test experienced significant process instabilities, including MEEs, fire within the hood, gas releases, power transients, and stuck electrodes. Changes made before initiating the second test included additional soil overburden, additional operational control of the electrodes, and an additional off-gas blower. The second test was much more stable than the first, allowing it to achieve its melting objectives.

After a 3-month period of cooling, the glass monoliths were exhumed and the glass sampled. The glasses exhibited leach rates approximately 10 times slower than typically observed for high-level waste glasses. The results of the tests also indicated that the capability of adding glass-forming materials or soil during ISV processing may be needed to improve the stability of the operation and prevent exposing the buried waste as subsidence occurs.